RETRACTED ARTICLE: Geo-environmental suitability assessment for tunnel in sub-deep layer in Zhengzhou

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In order to better provide geological basis for the rail transport planning in Zhengzhou, the geo-environmental suitability assessment for tunnel in sub-deep layer was carried out. In the study, the multi-objective linear weighted function method and analytic hierarchy process were used to evaluate the suitability of geological environment. The results show that the index affecting the geological environment suitability of tunnel in sub-deep layer in the study area mainly include the enriched layer of calcareous concretions, the weighted average compressive modulus, the standard deviation of compression modulus and the content of chloride ion in groundwater. The area with poor suitability of geological environment is mainly distributed in the southeast of the study area. During the construction in this area, the influence of the enriched layer of calcareous concretions and the stratum with poor uniformity on operation should be considered. The moderate suitability of geological environment is mainly consistent with the distribution of the enriched layer of calcareous concretions. Other areas in the study area are the good suitability of geological environment. In the future, the data precision in the evaluation should be improved, utilization of underground space should be got by remote sensing, and a relative-independent evaluation index system and dynamic evaluation model should be established.

Introduction

With the development of urbanization, the scale, population and the demand for land are increasing rapidly. The land scarcity has been restricting the sustainable development of cities and has become one of the bottlenecks of urban development. For most cities, most of the high-rise buildings and unlimited expansion of land are taken to meet the above phenomena. But the measures are limited. So the government turned to the underground space and managed it as a new-style land resource (Han & Antonia, 2019). Active and orderly development and utilization of underground space can effectively save urban land resources, reduce traffic congestion, population density and realize sustainable development of the city (Cui et al. 2012; Jacques, 2017; Nathan et al., 2018).

The development and utilization of underground space in China started in the form of Civil Air Defense Project in the early 1950s. With the development of the times, the development and utilization of underground space in China is developing step by step (Jiang et al., 2015). Since 1953, many cities in China began to plan and construct subway to bring convenience to people. According to statistics, by the end of 2018, 37 cities in China have completed 5539.19 kilometres of subway and China is at the front ranks of the world. Because of its economic rationality and technical advantages, shield method has become the most commonly used method in subway construction.

The existing research (Cao et al., 2019; Liu, Wu et al., 2017; 2014; Zhang et al., 2016; Yue, 2013) is to establish a unified evaluation index system for the different vertical levels and different operation methods in the study area. so that the evaluation index system established is not perfect. The geological conditions play a decisive role in the safety and economy of tunnel. In recent years, with the gradual increase of urban underground space, safety accidents occurred in in the process of underground engineering construction in many cities. the accidents were directly related to the geological conditions to a large extent. So the practice shows that evaluating the suitability of geological environment and solving the geological problems correctly are the foundation of reasonable development of tunnel. The paper evaluates the suitability of engineering geological environment of tunnel in the study area to provide geological basis for the scientific planning of Zhengzhou tunnel engineering through studying the geological environmental characteristics.

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Material and methods

The study area
Zhengzhou is located in the geographical centre of China. Zhengzhou is an important key position in china. It belongs to the zone of the continental monsoon climate and has four distinctive seasons. The distribution of precipitation is uneven in a year and mostly concentrated in July to September. The rivers in the area belong to the Yellow River and Huaihe River.

Topography and geomorphology
According to interpretation results of remote sensing (Sun, 2019), the high-lying south-west, north-eastern low terrain is controlled by the NW trending structure and near EW trending structure. So the geomorphologic landscape on the East and west sides of Beijing-Guangzhou Railway is different (Liu, Tian et al., 2017). The overall morphological shape is the plain, and only in the south of South-to-North Water Transfer Project the geomorphology is loess hilly. The geomorphology to the west of Beijing-Guangzhou Railway is the pre-mountain alluvial-proluvial plain and the east is Yellow River alluvial plain.

Formation lithology
The exposed strata in the area are mainly Quaternary. In the early Pleistocene of the Quaternary, Zhengzhou was in decreasing state of difference. A set of river and lake sediments were deposited in the front of the mountain in the southwest. In the early Middle Pleistocene, the piedmont area in the southwest was relatively uplifted and a set of alluvial proluvial sediments was deposited, and later the Aeolian Loess is deposited on it. Meanwhile the river and lake sediments deposits on the east area. In the late Middle Pleistocene, Yellow River cut through Sanmenhu and entered the North China Plain for stratum subsidence with small velocity. And a layer of early fluvial alluvial sand was generally deposited in Kaifeng Depression. In the late Pleistocene, the Yellow River alluvial fan is developed, and the sediments mainly coarse-grained. In Holocene, the features of Yellow River are wandering result in the thickness of the alluvial deposits is relatively small. Most of the surface sediments in the area are mainly the sediments of late Holocene, and the alluvial deposits in the early Holocene are distributed in high terrain area.

As a kind of special soil, the enriched layer of calcareous concretions is composed of calcium core and cohesive soil. The enriched layer brings great difficulty to tunnel construction for its typical mechanical instability. It is mainly distributed in the sub-deep layer in the form of honeycomb in the study area.

Geological structure
The study area is covered by Quaternary Strata and the geological structures are hidden structure. According to the previous research results of remote sensing and geophysical prospecting, the main structure is fault. The fault reveals two main directions as north-west and near east-west to control the geomorphology and Cenozoic sedimentation in the study area. The faults are inactive since Quaternary in the study area.

Hydrogeological conditions
Pore water in loose rock zone is the main groundwater type in the study area. The groundwater can be divided into shallow aquifer and middle deep aquifer according to the spatial distribution and burial depth of groundwater. Now the shallow aquifer is closely related to the development of underground space. The shallow aquifer is shallowly buried, and its floor depth is 45–55 m and more than 60 m in local area. The groundwater is phreatic water or micro artesian water. There is a group of silty clay or silt at a thickness of 25~45 m between shallow aquifer and middle deep aquifer. The shallow aquifer can be divided into pore water in sand and pore fissure water in clay.

Development and utilization of underground space
The underground space in Zhengzhou is divided into shallow underground space with the depth of 0 ~15 m, middle underground space with the depth of 15 ~30 m and sub deep underground space with the depth of 30 ~50 m according to “Zhengzhou underground space and civil defence master plan (2017–2035)”

At present, attached underground space in Zhengzhou is mainly within 15 m underground and mainly consists of one or two floors with the main function of construction and parking. The single built underground space includes underground transportation facilities, underground municipal facilities and civil defence. Among which, the underground passage and civil defence are generally developed within 10 m, the municipal utility tunnel is developed within 15 m, and urban rail transit is developed between 15 and 25 m underground.

Evaluation method of geological environment suitability
The suitability evaluation of geological environment is a comprehensive evaluation project of multi-index. Although there are many research methods proposed, the most widely used methods are multi-objective linear weighting function method, fuzzy comprehensive judgment method, grey clustering method, etc. In this study, multi-objective linear weighting function
method will be used to evaluate the geological environment suitability of sub-deep tunnel in Zhengzhou.

**Introduction of method**

The multi-objective linear weighting function method is widely used in all works at present, and its evaluation result is unanimously recognized. The mathematical model is as follows:

\[
P_I = \sum_{i=1}^{m} w_i u_i
\]

Among them, \( PI \) is the score of suitability evaluation, \( w_i \) is the weight of evaluation index, \( m \) is the number of indexes and \( u_i \) is the value of index.

**Evaluation steps**

①Each evaluation index is vectorized, then the map can be drew according to classification standard and the values are given to every region respectively based on the geographic information system.

②In this paper, the analytic hierarchy process is used to give the weight of primary index and secondary index in the evaluation index system of underground space suitability.

③The comprehensive evaluation map can be generated by piling up index zoning map one by one in the evaluation index system based on the geographic information system. The multi-objective linear weighting function method is used to calculate the suitability score of each evaluation unit. The suitability index score of each unit is analysed by clustering, and each evaluation unit is classified according to the clustering results;

④The evaluation map is adjusted properly according to the actual investigation and the boundary line of zone is smoothed., then the geological environment suitability evaluation map of underground space is obtained finally.

**Establishment of evaluation model**

**Evaluation index**

Shear stress of formation should be adopted to reflect operational difficulty of shield tunnelling for tunnel. but there is no experimental data about shear stress in the collected data, so 30–50 m underground weighted average compressive moduli is used to reflect the hardness of formation. The shield tunnelling operation is more difficult with the larger value of compressive moduli because the formation is harder.

The formation uniformity is an important index in tunnel operation. Because the environment is more uniform, the stress is more simple, the underground structure is more stable, and the hazards is not easy to happen. So tunnel operation in the same soil or similar soil is an ideal situation. The formation uniformity mainly considers the spatial difference of compression modulus. The sample standard deviation in multivariate statistics can reflect the dispersion of data. When the standard deviation is small, it reflects that the data is aggregated and indicates that the formation properties are similar. So the standard deviation of compression modulus of 30–50 m underground is chose as an index reflecting the formation uniformity.

At present, reinforced concrete is the main construction material. When the content of corrosive ions is higher resulting in reducing the durability and safety of water proof material and lining material (Xue, 2005). The slow corrosion of groundwater to underground structures is directly endangers the safety of structures (Loutfy et al., 2006) result in the increasing cost of engineering and maintenance. Therefore, the corrosion of groundwater should be brought into the evaluation index system when evaluating the suitability of underground space. In the collected groundwater quality data, the content of sulphate in groundwater in the study area is less than 500 mg/L. There is no change in the whole study area and the corrosivity of groundwater on concrete structure is weak according to code for investigation of geotechnical engineering GB50021-2009. But the content of chloride ion changes greatly in the study area. Therefore, the content of chloride ion in groundwater is selected as the evaluation index.

The enriched layer of calcareous concretions is a kind of special formation composed of calcareous concretions and cohesive soil. Its physical and mechanical properties mainly depend on the size and distribution of calcareous concretions. The enriched layer of calcareous concretions brings about difficulty for tunnel operation. The enriched layer of calcareous concretions is a typical unstable stratum. When the shield is driving in these layers, engineering accidents are easy to happen. During the shield operation of Zhengzhou Metro Line 2, the enriched layer of calcareous concretions results in unstable working parameters, full-load working, ground subsidence and equipment fault. Through the analysis of the collected data, the enriched layer of calcareous concretions is only found in the sub deep underground space with the distribution of honeycomb. So the enriched layer of calcareous concretions is regarded as an index for tunnel operation in sub deep layer.

In conclusion, the evaluation index system of geological environment suitability for sub deep tunnel project in Zhengzhou should be include weighted average compressive moduli and the standard deviation of compression modulus of 30–50 m underground, the content of chloride ion in groundwater and the enriched layer of calcareous concretions.
Zoning and scores of evaluation index

Figure 1–4 show the zoning map of each evaluation index. Table 1 shows the classification and scores of each evaluation index.

The determination process of evaluation index weights

In the study AHP is used to determine the weights of index. Firstly, the hierarchical structure of the evaluation index system should be established, and a number of experts are invited to judge the relative importance of each evaluation index in order to form the judgment matrix using 1–9 scale method. Secondly the max eigenvalue of the matrix and the corresponding eigenvector can be calculated. The eigenvector is normalized to get the index weight. Finally, the consistency test is carried out for the judgment matrix. When the consistency test is successful, the weight of the evaluation index calculated is reasonable. Otherwise, it will be repeatedly debugged to establish a reasonable judgment matrix and calculate the weight. Based on the above steps, the weight of the suitability evaluation index system of the sub deep underground space for tunnel project can be calculated.

The Table 2 shows that the weights of the enriched layer of calcareous concretions and the standard deviation of compression modulus are larger because the two index can cause the actual curve of the shield deviate from the design curve and make the operation difficult. The weight of the content of chloride ion in groundwater is small because the index has little impact on the operation.

Classification of suitability evaluation

Table 3 shows the suitability level standard of geological environment for underground space in subdeep layer.

Result and discussion

Suitability evaluation of geological environment for tunnel in sub deep layer

The suitability evaluation index of geological environment for tunnel is established and multi-objective linear weighting function method is adopted based on spatial analysis function of MAPGIS software. The Table 5 shows the geo-environmental Suitability assessment map for tunnel in the sub-deep layer.

It can be seen from Figure 5 that the distribution of the geological environment suitability assessment zoning is very similar to zoning map of the enriched layer of calcareous concretions. The reference revealed that the existence of the enriched layer of calcareous concretions has a great influence on shield operation.
It can be seen from Figure 5 that the area with poor suitability of geological environment is mainly distributed in the southeast of the study area, which accounts for 1% of the total area. In this area, the enriched layer of calcareous concretions is existed, the weighted average compressive modulus is greater than 10 MPa, the

referring to “construction techniques for a subway shield to pass through a calcareous-nodule-rich stratum”(Yao, 2018), and “key construction technology of shield crossing section area of sand and calcium nodules” (Li, 2015) and. Therefore, the evaluation result of geological environment suitability of sub deep underground space for tunnel is similar to the distribution of the enriched layer of calcareous concretions. The results is reasonable

Table 1. Grading and scores of evaluation index.

| Evaluation index                                      | Score | Score | Score | Score |
|-------------------------------------------------------|-------|-------|-------|-------|
| The weighted average compressive modulus (MPa)        | <10   | 10    | 3~6   | ≥6    |
| The standard deviation of compression modulus         | <3    | 10    | 7     | 6     |
| The content of chloride ion in groundwater (mg/L)     | <25   | 10    | 9     | 8     |
| The enriched layer of calcareous concretions          | Area with no enriched layer of calcareous concretions | Distribution area |
| Weight                                                | 0.2735 | 0.2956 | 0.1467 | 0.2842 |

Table 2. Weight assignation of evaluation index.

| Evaluation index                                      | Weight | Weight | Weight | Weight |
|-------------------------------------------------------|--------|--------|--------|--------|
| The weighted average compressive modulus              | 0.2735 | 0.2956 | 0.1467 | 0.2842 |
| The standard deviation of compression modulus         |        |        |        |        |
| The content of chloride ion in groundwater (mg/L)     |        |        |        |        |
| The enriched layer of calcareous concretions          |        |        |        |        |

Table 3. Classification standard of geo-environmental suitability.

| Classification of geo-environmental suitability | The good suitability of geological environment | The moderate suitability of geological environment | The poor suitability of geological environment |
|-------------------------------------------------|-----------------------------------------------|--------------------------------------------------|---------------------------------------------|
| PI                                              | 8~10                                         | 6~8                                              | Less than 6                                  |

Figure 4. Zoning map of the enriched layer of calcareous concretions.

Figure 5. Geo-environmental suitability assessment map for tunnel in sub-deep layer.
stratum uniformity is medium, and the content of chloride ion in groundwater is between 25 and 50 mg/L. The moderate suitability of geological environment is mainly consistent with the distribution of the enriched layer of calcareous concretions, which accounts for 15% of the total area. In this area the enriched layer of calcareous concretions is existed, the weighted average compressive modulus is less than 10MPa, the stratum is medium or uniform, and the content of chloride ion in groundwater is mainly between 25 and 50 mg/L.

Other areas in the study area are the good suitability of geological environment, which accounts for 74% of the total area. There is no enriched layer of calcareous concretions, the weighted average compressive modulus is less than 10MPa, the stratum is uniform, and the content of chloride ion in groundwater is mainly between 25 and 75 mg/L. Table 4 give the description of geo-environmental suitable areas.

There is no study about the suitability evaluation of geological environment for tunnel operation in China.

Conclusions

The conclusions are as follows through the comprehensive evaluation of geological environment suitability for tunnel in the sub deep layer in the study area:

(1) The evaluation index system of the geological environment suitability of the underground space for tunnel in sub deep layer in Zhengzhou is established based on the analysis of the geological environment conditions and tunnel construction technology. The evaluation index includes the enriched layer of calcareous concretions, the weighted average compressive modulus, the standard deviation of compressive modulus and the content of chloride ion in groundwater.

(2) The weight of each evaluation index reflects the contribution of each index on the suitability classification of underground space. For tunnel operation in sub deep layer, the weights of the enriched layer of calcareous concretions and the standard deviation of compression modulus are larger than the content of chloride ion in groundwater. It is illustrated that the influence of the enriched layer of calcareous concretions and the standard deviation of compression modulus on tunnel operation is significant, and the influence of groundwater corrosiveness is not obvious.

(3) In the comprehensive evaluation results of the geological environment suitability for tunnel in sub deep layer, the areas with good suitability are mainly distributed in the study area, the areas with moderate suitability are secondary, and the areas with poor suitability are distributed in a small area. In the area with poor suitability, the enriched layer of calcareous concretions is existed, the stratum is relatively hard and uniform, and the area is 4.2 km². The distribution of moderate suitable area is relatively consistent with that of the enriched layer of calcareous concretions, the stratum is uniform and soft, and the area is 64.0 km². There is no enriched layer of calcareous concretions in the area with good suitability. The evaluation results of the geological environment suitability showed that the geological environment conditions of Zhengzhou in sub deep layer are suitable for the tunnel operation.

(4) Existing underground space is not included in the study. remote sensing technology can be used to extract the height of buildings for roughly calculating the depth of the impact of buildings to identify the utilization of underground space. Finally, the database of the utilization of underground space is set up. In the planning process of underground space, the database of existing underground space and geological environment conditions are combined to guide the rational development of underground space in different layer in Zhengzhou.

(5) There are some shortcomings in the paper. We should strengthen the cooperation of all departments to improve the quality of data for the better evaluation. Besides, the current situation of the underground space construction is not considered in the index system. The database of the utilization of underground space should be established before the evaluation.

Table 4. Specification table of geo-environmental suitable areas.

| Evaluation zoning                          | The poor suitability of geological environment | The moderate suitability of geological environment | The good suitability of geological environment |
|-------------------------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Area (km²)                                | 4.2                                           | 64.0                                            | 369.6                                         |
| The enriched layer of calcareous concretions | Calcareous concretions enriched | Enriched calcareous concretions accounts for 73% of the area | No calcareous concretions                     |
| The weighted average compressive modulus  | More than 10 MPa                              | Mainly less than 10 MPa                         | Mainly less than 10 MPa                      |
| The standard deviation of compression modulus | It has medium formation uniformity             | The formation uniformity is mainly good and medium is the second | It has good formation uniformity               |
| The content of chloride ion in groundwater | The content of chloride ion is 25—50 mg/L     | The content of chloride ion is less than 75 mg/L and mainly between 20 and 50 mg/L | The content of chloride ion is mainly between 25 and 75 mg/L |
A relatively independent evaluation index system and a dynamic evaluation model for the suitability of underground space geological environment in different development stages should be established in the future.

Disclosure statement
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References
Cao, H., Yang, H. Y., Jiang, W., Ye, J. L., He, D. F. et al. (2019). The geological environment suitability assessment of underground space development in Changsha city. China Mining Magazine, 28(S2), 142–147. doi:10.12075/j.issn.1004-4051.2019.52.116

Cui, L. S., Shao, L., & Li, C. Q. (2012). Research on development and utilization of underground space in Zhengzhou City. Resources Guide, 02, 18–19. doi:10.3969/j.issn.1674-053X.2012.02.009

Han, A., & Antonia, C. (2019). Future cities, resilient cities – The role of underground space in achieving urban resilience. Underground Space.

Jacques, B. (2017). Cities think underground – Underground space (also for people. Procedia Engineering, 209, 49–55. https://doi.org/10.1016/j.proeng.2017.11.129

Jiang, L. B., Xia, M. M., & Cao, W. J. (2015). Discussion on the development and utilization of urban underground space in Zhengzhou City. Science and Technology, 25(22), 36. doi:10.3969/j.issn.1672-8289.2015.22.030

Li, T. J. (2015). Key construction technology of shield crossing section area of sand and calcium nodules. Value Engineering, 34(016), 115–117. doi:CNKISUN/ZGCG.0.2015-16-042

Liu, H. Z., Tian, Y., & Yang, P. (2017). A discussion of the construction technology of pumping and injection wells in the fine particle sediment distribution area. Hydrogeology & Engineering Geology, 44(001), 36–40+56. doi:10.16030/j.cnki.issn.1000-3665.2017.01.06

Liu, Y. L., Wu, J. P., Peng, P. Y. (2017). Suitability evaluation for the utilization of underground space in consideration of geo-environmental factors. Journal of Yangtze River Scientific Research Institute, 034(005), 58–62,67. doi:10.11988/ckyyb.20160182

Nathan, D., Mark, B., & Nelson, J. D. (2018). Going underground: An exploration of the interfaces between underground urban transport infrastructure and its environment. Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research, 81(NOV.), 450–462. doi:10.1016/j.tust.2018.08.027

Sun, H. C. (2019). Research on applications of remote sensing technology in cities: Taking Zhengzhou as an example. Jiangsu Science & Technology Information, 036(011), 60–62. doi:10.3969/j.issn.1004-7530.2019.11.016

Xue, Z. Y. (2005). Corrosion of building foundations caused by groundwater in red beds area and prevention measures: Case study for the city of Tianshui. Journal of Engineering Geology, 02, 183–188. doi:10.3969/j.issn.1004-9665.2005.02.008

Yao, Z. H. (2018). Construction techniques for a subway shield to pass through a calcareous-nodule-rich stratum. Traffic Engineering and Technology for National Defence, 016(001), 45–47+64. doi:10.13219/j.gjgyat.2018.01.012

Yue, Z. H. (2013). The suitability grey comprehensive evaluation about Shijiazhuang City underground space development and utilization. Hebei University of Technology.

Zhang, J. J., Ma, C. M., Kuang, H., Zhou, A. G., & Xia, Y. (2016). Geo-environmental suitability assessment with variable weight for underground space exploitation in Zhengzhou. Hydrogeology & Engineering Geology, 43(2), 118–125. doi:10.16030/j.cnki.issn.1000-3665.2016.02.18