J. Electrical Systems 20-2 (2024): 292-303

[1]Lin Guo
[2,*]Xiaojing Guo
[3]Shasha Liu
[4]Xinlin He
[5]Hui Tang
[6]Ruiyang Li
[7]Xiaoyu Ma

Geo-environmental Suitability Assessment for Shallow Foundition Pit in Urban Zhengzhou City Based on GIS and AHP Methods

Abstract: - With the objective of the security and sustainability of underground space, the geo-environment suitability assessment for shallow foundation pit was conducted by GIS and AHP methods combining with the characteristics of the study area on the basis of the investigation of the current exploitation of underground space and the geological environment conditions in Zhengzhou City and the advanced experiences at home and abroad. Computer technology provides powerful tools and methods to the geo-environmental suitability assessment of underground space, and supports decision-making and planning. In the research, the suitability of geo-environment was assessed using the multi-objective linear weighted function model. The results indicate that the elements influencing the geo-environment suitability of shallow foundation pit in the study area mainly include stability of foundation pit, active earth pressure of slope, and shallow groundwater depth and water enrichment of aquifer according to the impact of evaluation factors on the foundation pit engineering. The results showed that the suitable area with an area of about 96.2 km2 is located to the west of Beijing–Guangzhou Railway, the medium-suitable area with an area of about 174.4 km2 is located to the east of Beijing–Guangzhou Railway and to the west of the Beijing-Guangzhou high-speed railway, the poor-suitable area with an area of about 111.3 km2 is located to the east of Dongfeng canal-Jingguang high-speed Railway and we should particularly focus on the impact of surface water, groundwater, soft soil and land subsidence during construction. The application of GIS and AHP method provided key technical support for the assessment. The geo-environment suitability evaluation of the foundation pit engineering by GIS and AHP methods has a strong pertinence and can offer technical assistance for the exploitation of underground space in Zhengzhou City.

Keywords: Geo-environmental Suitability, Underground Space, Evaluation Model, GIS and AHP Methods, Foundation Pit, Zhengzhou.

I. INTRODUCTION

The scale and population of cities are expanding rapidly due to the quick growth of the urban economy in China. The rapid urbanization process made the original infrastructure of cities can't meet demand and resulted in problems such as crowed space, traffic jams, aggravating circumstances, etc. The current response measures were high-rise buildings and expansion of cities, but it is nevertheless finite. So, it is necessary to expand the space into underground to make the city sustainable [1-2]. Since 2000, massive exploitation of underground space has been underway. In recent years, some cities, such as Shanghai, Nanjing and Hangzhou, etc, had safety accidents of different degrees during the construction. One reason is that the insufficient work for the evaluation and planning of underground space. So, it is imperative to conduct the research about the geo-environment suitability assessment in the exploitation of underground space. Currently the evaluation research is excessively simplistic, and the applicability of the results is weak. The influence mechanisms of geological environment conditions on tunnel engineering and foundation pit engineering is different. The foundation pit is the primary types of exploitation utilization and is a necessary process for underground construction. So the geological environment assessment of foundation pit engineering is very meaningful for planning the exploitation of underground space in cities.

[1] Henan Academy of Geology, Zhengzhou, 450001; Henan Key Laboratory of Prevention and Remediation of Groundwater Pollution, Zhengzhou, 450001
[2] Henan Academy of Geology, Zhengzhou, 450001; Henan Key Laboratory of Prevention and Remediation of Groundwater Pollution, Zhengzhou, 450001
[3] Henan Academy of Geology, Zhengzhou, 450001; Henan Key Laboratory of Prevention and Remediation of Groundwater Pollution, Zhengzhou, 450001
[4] Henan Academy of Geology, Zhengzhou, 450001; Henan Key Laboratory of Prevention and Remediation of Groundwater Pollution, Zhengzhou, 450001
[5] Henan Academy of Geology, Zhengzhou, 450001
[6] Henan Institute of Geological Sciences, Zhengzhou, 450001
[7] Henan Academy of Geology, Zhengzhou, 450001; Henan Key Laboratory of Prevention and Remediation of Groundwater Pollution, Zhengzhou, 450001
*Corresponding author: Guo Xiaojing

Computer technology plays an important role in the geo-environmental suitability assessment of underground space. Computer technology can help process and analyze large amounts of geo-environmental data to achieve automation and efficiency in processing and analysis of data. Computer technology can establish models for the suitability assessment of underground space and simulate and predict assessment results [3]. Computer technology can be used to conduct the multi-factor analysis of the suitability assessment of underground space. Through the processing and calculation of a large amount of data, computer technology can achieve weight distribution and comprehensive assessment of multiple factors. Computer technology can present the results of the suitability assessment of underground space through visualization and interaction. Computer technology can help decision-makers better understand and interpret assessment results by presenting assessment results in maps, charts, three-dimensional models, and other visual forms. Computer technology can provide efficient database management systems to make data access more convenient and rapid. In conclusion, the importance of computer technology in the geo-environmental suitability assessment of underground space cannot be ignored.

Research on underground spaces in foreign countries has been extensive and in-depth in academia and in practical applications [4-6]. Geo-environmental suitability assessment of the exploitation of underground space are carried out in large and medium-sized cities in China. But there was no evaluation of different layers [7-8]. In recent years, the geo-environmental suitability assessment of different layers has begun [9] and there is no assessment for different construction methods. The distribution characteristics of sensitive factors related to geology in urban underground space of Zhengzhou has been studied [10]. There are several studies establishing a unified evaluation index system [11-13] and made the evaluation index system general. The studied are made about the suitability assessment for tunnel engineering at different vertical levels in Zhengzhou based on the geo-environmental characteristics [14-15]. Foundation pit engineering is the main method of underground space development. No suitability assessment for foundation pit engineering has been carried out. The study analyzes the geo-environmental suitability of shallow foundation pit through studying the characteristics of the geological environment and can offer geological evidence for the planning and decision-making department of government in Zhengzhou.

II. Material and Methods

A. The Study Area

Zhengzhou has superior geographical conditions and is located in the central plains and in the national economic hinterland. At the national level, Zhengzhou is a key node in the north-south intersection and has a very important strategic position.

Zhengzhou has a temperate continental monsoon climate with characters of distinct four seasons and simultaneous rainfall and warmth. Zhengzhou is located in the southern part of the Yellow River and belongs to the Huai River Basin. There are many rivers in Zhengzhou. The topography in most parts of the city is the plain landform and it is the loess hill landform only in the southwest. The plain landform is divided into alluvial plain and delta plain according to its formation. The lithology in the underground space development layer is mainly quaternary. The main geological structure are hidden faults and most of which are inactive faults formed before the Neogene period. The groundwater in the underground space development layer are mainly shallow pore water in loose rocks.

By the end of 2017, the overall underground space in Zhengzhou City was 28,462,800 m^2. Attached underground space mainly focuses on one or two levels and some of them extends to three or four levels. The development depth is mainly within 15 meters below ground and the main function is parking or business. The individual underground space encompasses transport facilities, civic infrastructure, and civil defense projects in the underground. There are developments of underground passages and civil defense projects within a distance of 10 meters, Integrated pipe gallery for unban infrastructure are developed within a range of 15 meters, and the development of urban rail transit falls within a range of 15 to 25 meters.

B. Geo-environment Suitability Evaluation Model

The assessment of geo-environmental suitability for the exploitation of underground space is a comprehensive study in the field of geotechnical engineering. Its assessment indexes involve geology, hydrogeology, engineering geology, and environmental geology, etc. The indexes includes qualitative factors and quantitative factors. In this study, based on the geological environmental conditions and the major encountered during the excavation of foundation pit construction, the suitability of a shallow foundation pit was calculated considering different degrees of impact by geological influencing factors in the research area [16-17].

The model is shown as follows:

$$PI = \sum_{i=1}^{m} w_i \sum_{j=1}^{n} w_{ij}\, u_{ij} \tag{1}$$

PI refers to the score of suitability, w_i is the weight assigned to the primary index, *m* is the total number of primary indices, *n* is the total number of secondary indices, w_{ij} is the weight of the *jth* secondary factor in the *ith* primary factors, U_{ij} is the value of the *jth* secondary factor in the *ith* primary factors.

C. Evaluation Process

1) Evaluation index

The slope of the terrain and elevation of the ground surface are not significantly affected the foundation pit engineering. The fracture is not important according to its depth and characteristics. Therefore, the slope of the terrain, elevation of the ground surface and the fracture are not included in the assessment index system.

a) Engineering geological conditions

The critical height of the foundation pit slope in a state of ultimate equilibrium is an important basis for evaluating slope stability and designing slope structures. The calculation of the critical height is particularly necessary in cities when slope construction is impossible due to limitations of site conditions. The calculation of soil pressure is an important issue in the design of foundation pit engineering. Its calculation adopts the Rankine theory in the study. The compressive modulus of the soil reflects soil deformation characteristics when compressed under vertical stress. A smaller compressive modulus indicates a larger soil compressive coefficient resulting in significant deformations, uneven subsidence, and excavation slope collapse, etc. the small compressive modulus is unsuitable for underground space development. The more uniform the formation makes the structure more stable. The construction difficulty of underground engineering is relatively lower. Cracks, instability, and other phenomena are not easy to occur during the construction. The uniform of the strata is reflected by the standard deviation of the compressive modulus. The cohesive strength and internal friction angle of the soil have the significant impact on the slope of foundation pit in the analysis of slope stability [18]. Therefore, the critical height of the slope, active earth pressure of slope, the thickness-weighted average compressive modulus, stratum uniformity, and slope stability are selected to the geological conditions of foundation pit construction.

b) Hydrogeological conditions

The buried depth of the groundwater has a significant impact on the exploitation of underground space. Firstly, it affects the construction of underground engineering. Secondly, the buoyant force caused by groundwater applied to the structures underground. If the water of the aquifer is sufficient, the difficulty of groundwater control during construction and the cost of waterproofing measures and drainage measures will be increase. Also, it can also impact the later use and operation of the underground space. The chemical substances in groundwater affect the durability and safety of the materials for underground buildings and increase the cost of construction and maintenance. In groundwater the Cl- content varies significantly while the SO42- content is similar based on the collected data. Therefore, Cl- content are chosen as an indicator that indicate the tendency of groundwater to cause corrosion. Rivers has adverse effects on nearby foundation pit constructions and easily induce sand slugs and surging in pipelines. The difficulty and is the risk of construction is relatively high. Meanwhile, the underground buildings will remain below the surface water body for an extended period and threatened to some extent by surface water. Groundwater depth, water enrichment of aquifer, Cl- content in groundwater, and surface water are selected to reflect the hydrological conditions of foundation pit construction.

c) Environmental geological conditions

After excavation, the soft soil in the foundation pit loses its lateral constraint. Plastic flow and compressive deformation of soft soil occurs. It can lead to uneven ground settlement, slope instability, and deformation of support structures. The loose and saturated sand will lose its shear strength and bearing capacity instantly under the action of vibration.it is sand liquefaction. The phenomenon of sand liquefaction has negative repercussions on the building and functioning of subterranean structures. Ground subsidence has a wide range of influence and occurs at a slow rate and is not easily noticeable. However, ground subsidence can made the buildings including above-ground buildings and underground structures tilted, cracked or collapse and made the other water inflow. The loess has high strength and low compressibility when its moisture content is natural. Its structure will be damaged when it is saturated with water and leading to underground building damage. In conclusion, soft clay thickness, collapsible loess, sand liquefaction and ground subsidence are selected as environmental geological factors affecting the development of underground spaces.

d) Current status of ground construction

According to the theory about foundation, underground spaces requires maintaining a specific horizontal and vertical clearance from already-existing structures. Because of dense concentration of surface and underground structures and the complex underground pipelines in urban central areas, the excavation of foundation engineering may cause the tilting, cracking or collapse of nearby buildings. So surface and underground structures restrict the excavation of foundation pit engineering. The database of underground buildings has not been established so it is not within consideration [19]. Therefore, the current situation of surface building is a factor that affects the exploitation of underground engineering.

e) Sensitive area

The prohibited construction areas in the overall urban planning of Zhengzhou between.2012 and.2030 will be participating in the suitability assessment as a sensitive factor. The prohibited construction areas include protected area of water sources, major rivers, reservoirs, cultural relics and major flood channels. The sensitive factors will be evaluated using one ballot veto. When any of these factors is existed the areas is unsuitable for development and utilization of underground space. Additionally, if there are important mineral resources with clear registration of mining rights in the study areas, the mining area should be directly designated as an unsuitable areas [20].

2) Classification of evaluation index and assignment criteria

The zoning map in Figure 1-16 illustrates the spatial distribution of each evaluation index.

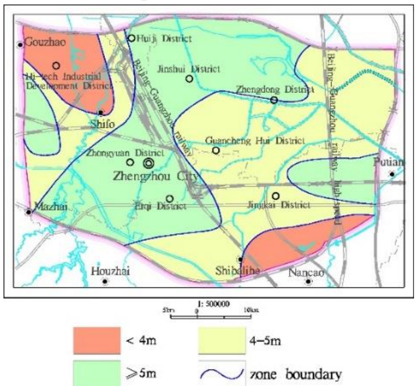

Figure 1: Zone Map of the Critical Height of Foundation Pit

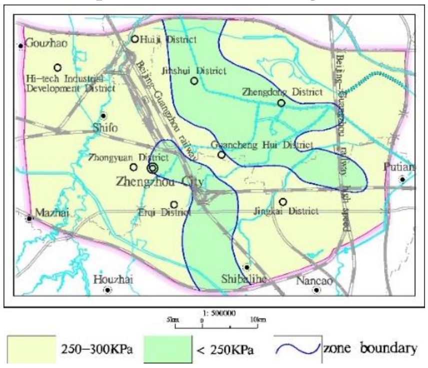

Figure 2: Zone Map of Active Soil Pressure on Slopes

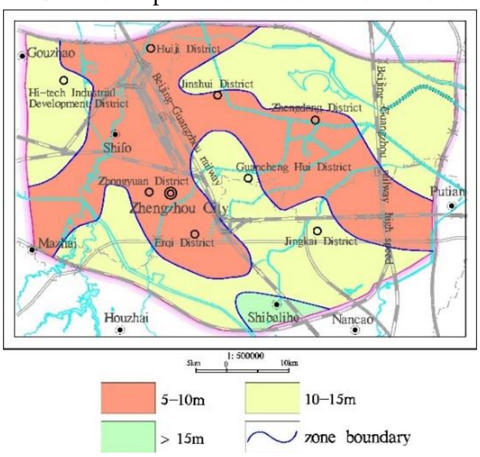

Figure 3: Zone Map of the Thickness-weighted Average Compressive Modulus

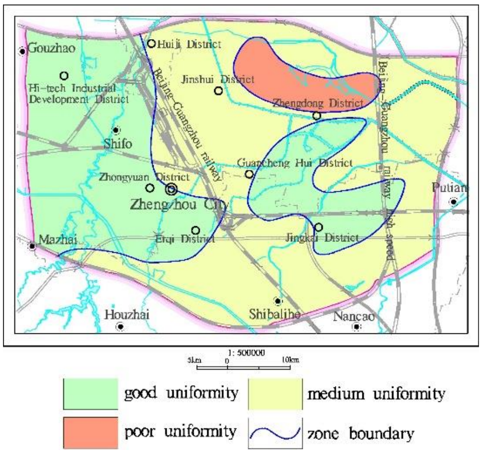

Figure 4: Zone Map of Uniform of the Strata

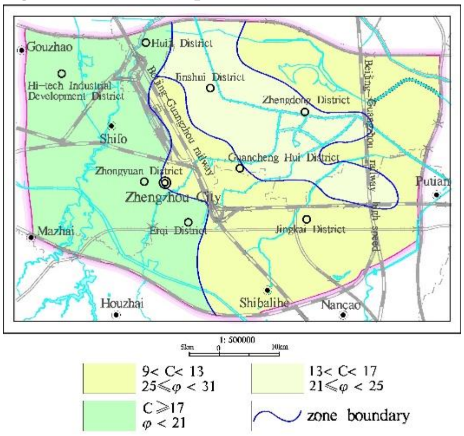

Figure 5: Zone Map of Slope Stability

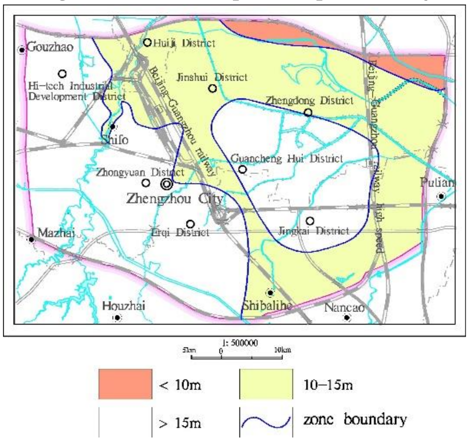

Figure 6: Zone Map of Groundwater Depth

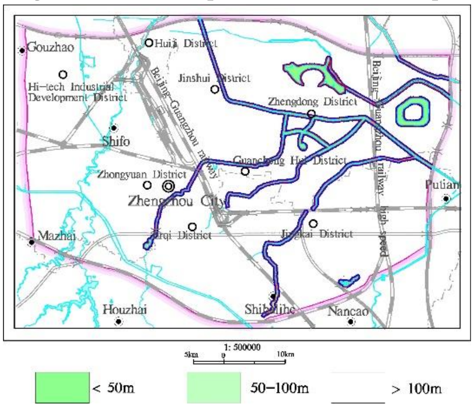

Figure 7: Zone Map of Surface Water

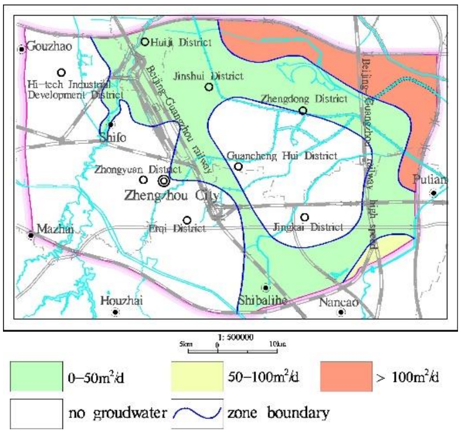

Figure 8: Zone Map of Aquifer Enrichment

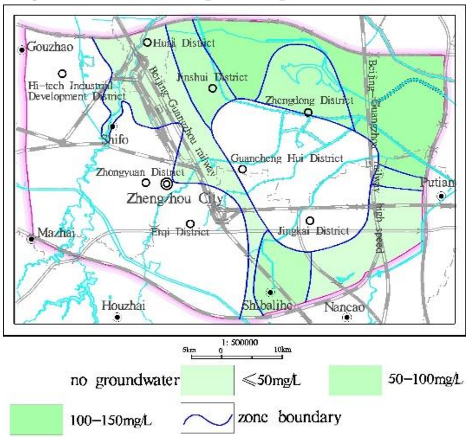

Figure 9: Zone Map of Cl- in Groundwater

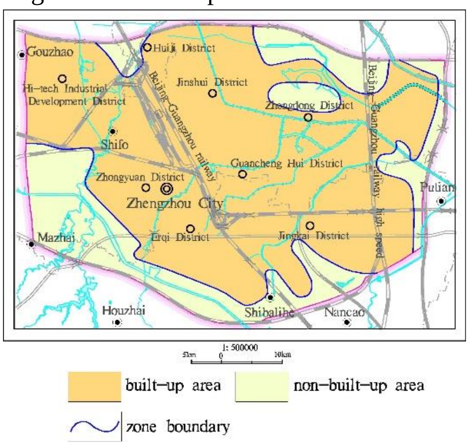

Figure 10: Zone Map of Build-up Area

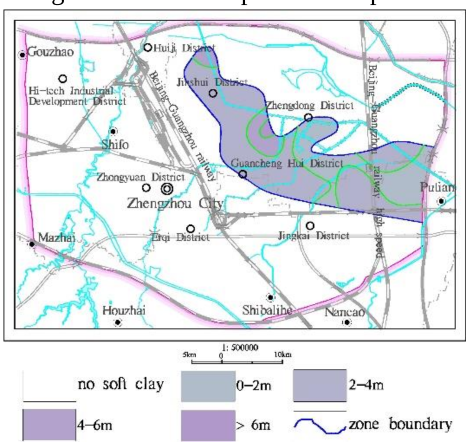

Figure 11: Zone Map of Soft Clay Thickness

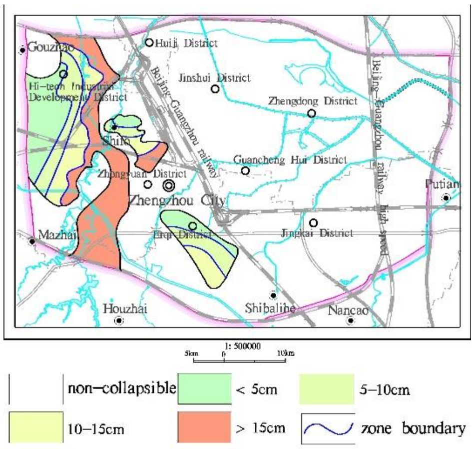

Figure 12: Zone Map of Collapsible Loess

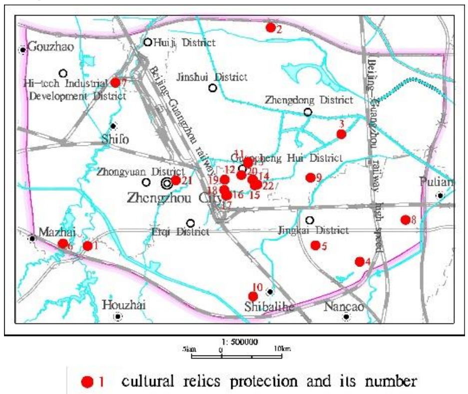

Figure 13: Zone Map of Cultural Relics Protection

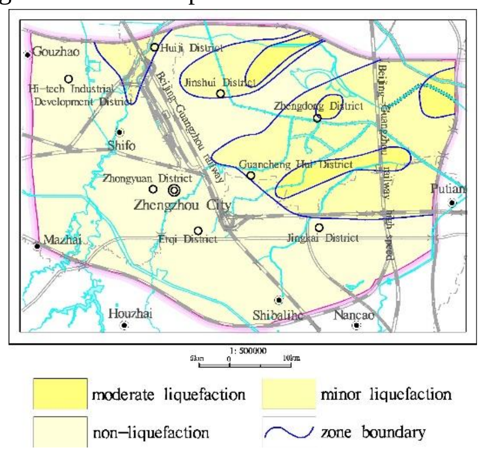

Figure 14: Zone Map of Sand Liquefaction

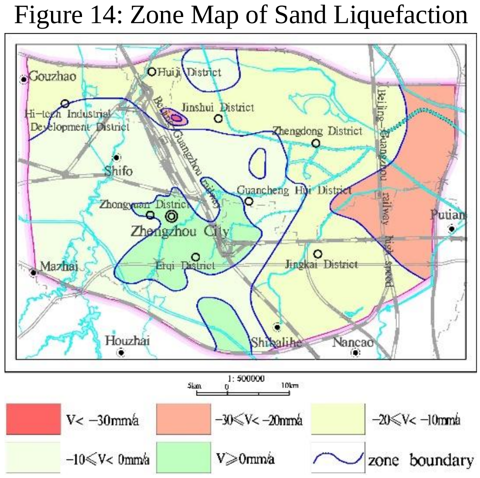

Figure 15: Zone Map of Ground Subsidence Rate

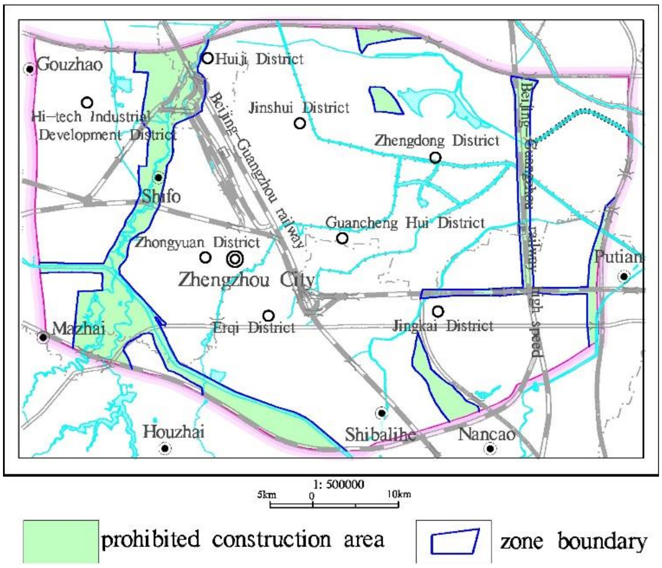

Figure 16: Zone Map of Prohibited Construction Areas

Table 1 shows the classification and scores of factors.

Table 1: Classification and Scores of Factors

the critical height of slope(m)	≥5	4～5	<4		
score	7	5	3		
active soil pressure on slopes (KPa)	<250	250～350			
score	7	5			
the thickness-weighted average compressive modulus (MPa)	≥15	10～15	<10		
score	9	7	3		
the variance in the compressive modulus	<3	3～6	≥6		
uniform of the strata	good uniformity	medium uniformity	Poor uniformity		
score	10	7	3		
cohesive strength(KPa)	C≥17	13≤C＜17	9≤C＜13		
internal friction angle(°)	<21	21≤φ＜25	25≤φ＜31		
slope stability	Good stability	moderate stability	poor stability		
score	9	7	5		
groundwater depth (m)	>15	10～15	<10		
score	10	7	3		
Hydraulic conductivity (m^2/d)	areas without groundwater	0～50	50～100	>100	
score	10	7	5	3	
Cl- in groundwater (mg/L)	areas without groundwater	＜50	50～100	>100	
score	10	7	5	3	
Distance to the surface water(m)	>100m	50～100m	<50m		
score	10	7	3		
soft clay thickness (m)	0	0～2	2～4	4～6	>6
score	10	7	5	3	1
sand liquefaction	non-liquefaction	minor liquefaction	moderate liquefaction		
score	10	5	3		
ground subsidence rate (mm/a)	≥-10	-20～-10	-30～-20	＜-30	
score	9	7	3	1	
The settlement of collapsible loess(cm)	0	0～5	5～10	10～15	>15
score	10	7	5	3	1
existing buildings	non-built-up area	built-up area			
score	10	5			

3) Calculation of weights of factors

The weights are determined by the Analytic Hierarchy Process (AHP) [21]. A rational judgment matrix is established by iteratively debugging. Subsequently, the principal eigenvector and its corresponding maximum eigenvalue are determined through matrix calculations. Finally, the eigenvector is normalized to derive the weight for each factor. The result is as illustrated in Table 2.

Table 2: Weight Distribution of Evaluation Factors

primary index	weight	secondary index	weight
Engineering Geological Conditions	0.5177	active soil pressure on slopes	0.1841
		the critical height of slope	0.1375
		the thickness-weighted average compressive modulus	0.1333
		uniform of the strata	0.1067
		slope stability	0.4384
Hydrogeological Conditions	0.2553	groundwater depth	0.3584
		Hydraulic conductivity	0.3015
		Cl- in groundwater	0.2301
		Distance to the surface water	0.1100
Environmental Geological Conditions	0.1695	soft clay thickness	0.2914
		sand liquefaction	0.2451
		ground subsidence rate	0.3741
		The settlement of collapsible loess	0.0894
Current Situation of ground buildings	0.0575	existing buildings	1

4) *Classification of suitability.*

The classification criteria of suitability is shown in Table 3.

Table 3: Classification Criteria of the Suitability

The score of suitability	good suitability	moderate suitability	poor suitability
PI	8～10	6～8	Less than 6

III. RESULTS

The map of geo-environment suitability evaluation for shallow foundation pit is got by the above method using MapGIS on the basis of the preexisting index system. The result is seen in Figure 17 for details.

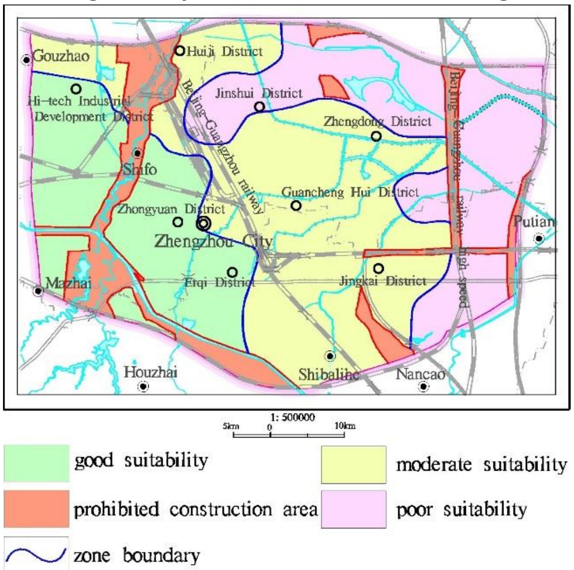

Figure 17: The Map of Geo-environment Suitability Evaluation for Shallow Foundation Pit

Figure 17 shows that the geo-environment suitability for shallow foundation pit is mainly categorized into four levels.

IV. DISCUSSION

The regions with good suitability are predominantly located to the west of Jingguang railway; the moderate suitability area is mainly distributed on the eastern side of Jingguang railway and the west of Beijing-Guangzhou high speed railway; the regions with poor suitability are primarily located in the eastern part of Dongfengqu. And Jingguang rapid transit railways. The unsuitable areas are mainly including the protection area of Changzhuang reservoir, Xiliuhu reservoir, the primary protection area of South-to-North Water Diversion Project, protection range of cultural relics, as well as control zone of large-scale infrastructure corridors.

The characteristics of Geo-environmental suitability zones are detailed in Table 4.

Table 4: Description of Suitability Evaluation Units

Assessment units	Engineering Geological Conditions	Hydrogeological Conditions	Environmental Geological Conditions	Current Situation of ground buildings
good suitability(96.2 km^2,22.0percent)	The critical height of slope is mainly greater than 5 meters. The active soil pressure on slopes is between 250 and 350 KPa. The average compressive modulus, calculated by taking into account the thickness, is below 15 MPa. The geological layers are uniform. The thickness-weighted average cohesion strength is greater than or equal to 17, and the thickness-weighted average internal friction angle is less than 21.	The groundwater depth is more than 15 meters. There is no groundwater within a depth of 15 meters underground. The impact range of surface water accounts for only 1 percent of the total area.	There is no soft clay and liquefiable sand in the stratum .The ground subsidence rate is greater than -10 mm/a. 53 percent of the area is covered by collapsible loess soil. The total settlement is mainly less than 5 cm and greater than 15 cm.	The built-up area accounts for 60 percent of the total area.
moderate suitability(174.4km^2,39.8 percent)	The critical height of slope is mainly between 4 and 5 meters. The active soil pressure on slopes is less than 350 KPa. The average compressive modulus, calculated by taking into account the thickness, is below 15 MPa and mainly between 5 and 10 MPa. The uniformity of strata is mainly moderate.	The groundwater depth is more than 10 meters. 54percent of the area in the study has no groundwater within a depth of 15 meters underground, and the hydraulic conductivity of areas with groundwater is less than 50 m2/d. The Cl- content of groundwater is mainly less than 100 mg/L. The impact range of surface water accounts for 7 percent of the total area.	The area of soft clay accounts for 23 percent of assessment unit, and the thickness is mainly between 2 and 4 meters. The sand is mainly non-liquefiable. The ground subsidence rate is less than -10 mm/a.7 percent of the area is covered by collapsible loess soil. The total settlement is mainly less than 15 cm.	The built-up area accounts for 86 percent of the total area.
poor suitability(111.3 km^2,25.4 percent)	The critical height of slope is mainly less than 5 meters. The active soil pressure on slopes is mainly between 250 and 350 KPa. The average compressive modulus, calculated by taking into account the thickness, is below 15 MPa. The level of uniformity in the geological layers is primarily classified as moderate.	The groundwater depth is mainly between10 and 15 meters. The hydraulic conductivity of groundwater is mainly less than 50 m2/d. The concentration of chloride ions in the groundwater mainly falls within the range of 100 to 150 milligrams per liter. The impact range of surface water accounts for 9 percent of the total area.	The area of soft clay accounts for 25 percent of assessment unit, and the thickness is mainly less than 4 meters. The sand is mainly non-liquefiable and slight liquefaction. The ground subsidence rate is between -30 and -20 mm/a. There is no collapsible loess soil.	The built-up area accounts for 69 percent of the total area.
prohibited construction areas(55.9 km^2, 12.8 percent)	The area includes the protection area of Changzhuang reservoir, xiliuhu reservoir, the primary protection area of South-to-North Water Diversion Project, protection range of cultural relics, as well as control zone of large-scale infrastructure corridors.			

V. CONCLUSIONS

Based on the above-mentioned assessment, the following conclusions can be deduced.

The geo-environmental suitability evaluation index system of shallow foundation pit was constructed by choosing appropriate evaluation factors selectively based on the geological environmental conditions that influence the development of shallow foundation pit. The geo-environmental suitability evaluation index system in the paper was including five primary indicators and 16 secondary indicators. The primary indicators included engineering geological conditions, hydrogeological conditions, environmental geological conditions, current situation of ground buildings, and the prohibited construction areas. The secondary indicators included the critical height of foundation pit, uniform of the strata, groundwater depth, aquifer enrichment, soft clay thickness, collapsible loess, etal.

The weights represent the contribution to the suitability of foundation pit. Slope stability has the most significant impact on excavation of foundation pit, and its weight is also the highest. Active soil pressure on slopes, groundwater depth, aquifer enrichment have significant impacts, and its weight is relatively high. Other factors are not important.

The assessment results for shallow foundation pit is that most of the areas have a moderate suitability and regions with poor suitability are subordinate. The characteristics of the area with good suitability are good. When selecting the location for major construction projects, efforts should be made to avoid areas with poor geo-environmental suitability. While constructing shallow foundation pit in areas with moderate geo-environmental suitability, it should be pay attention to issues, such as soft clay, sand liquefaction, ground subsidence, etal. In summary, the geo-environmental conditions for foundation pit in Zhengzhou city are generally moderate, and adverse factors affecting construction are existed. Government agencies should attach importance to these adverse factors.

The advantages of computer technology in the assessment of geo-environmental suitability of underground space can be seen in data processing and analysis, model development and prediction, multi-factor analysis and decision support and visualization and presentation. These advantages provide strong support and tools for the scientific evaluation and rational planning of underground spaces.

ACKNOWLEDGEMENT

The study was supported by the “Geological Survey of Various Elements in Luoyang City and Zhengzhou City at a Scale of 1:25,000”, “Study on the Investigation and Evaluation of Underground Space Development and Utilization in Zhengzhou City” and “Construction of Urban Geology Big Data Application System and Technical Standard System.”(2023-331-XM027-KT01).

REFERENCES

[1] Admiraal H, Cornaro A. Why underground space should be included in urban planning policy and how this will enhance an urban underground future. Tunnelling and Underground Space Technology, 2016, 55:214-220.

[2] Wout Broere. Urban underground space: Solving the problems of today’s cities. Tunnelling and Underground Space Technology, 2016, 55: 245-248.

[3] Zhao Shuxin. Application of computer technology in mathematical modeling. Electronic Technology, 2023, 52(01):284-285.

[4] Tengborg P, Sturk R. Development of the use of underground space in Sweden. Tunneling and Underground Space Technology, 2016, 55: 339-341.

[5] Konykhov D S, Kolybin I V. Principles of the integrated development of Moscow City underground space. IOP Conference Series: Earth and Environmental Science, 2021, 703(1).

[6] Youssef A M, Pradhan B, Tarabees E. Integrated evaluation of urban development suitability based on remote sensing and GIS techniques: contribution from the analytic hierarchy process. Arabian Journal of Geosciences, 2011, 4(3-4): 463-473.

[7] Deng Fei, Pu Jian , Huang Yu ,Han qingding.3D geological suitability evaluation for underground space based on the AHP-cloud model. Underground Space, 2023,8:109-122.

[8] Kaliampakos D,Benardos A,Mavrikos A. A review on the economics of underground space utilization. Tunneling and Underground Space Technology, 2016, 55(1): 236-244.

[9] Su Dong , Huang Maolong, Han Wenlong , Li Aiguo, Wang Enzhi, Chen Xiangsheng. Suitability evaluation of underground space development in Shenzhen: urban geo-environmental considerations. Earth Science Frontiers, 2023, 30(04):514-524.

[10] Wu Binghua, Guo Lin, Kou Yafei, Li Na, Tang Hui. Distribution characteristics of sensitive geological factors in urban underground space of Zhengzhou. Science Technology and Engineering, 2019, 19(36):94-98.

[11] Xia You, Ma Chuanming. Geo-environmental suitability assessment of underground space resources exploitation and utilization in Zhengzhou City. Chinese Journal of Underground Space and Engineering, 2014, 10(03):493-497.

[12] Zhang Jingjing, Ma Chuanming, Kuang Heng.2016. Geo-environmental suitability assessment with variable weight for underground space exploitation in Zhengzhou. Hydrogeology & Engineering Geology, 43(02):118-125.

[13] Zhang Runhua, Cheng Yuanyuan, Liu Congcong. Study and analysis on suitability evaluation and development threshold of underground space in Zhengzhou. Water Resources & South-to-North Water Diversion, 2021,50(02):74-76.

[14] Guo Xiaojing, Guo Lin, Wu Binhua. Yang Po, Kou Yafei, Li Na, Tang Hui. Geo-environmental suitability assessment for tunnel in the middle layer in urban Zhengzhou city. Science technology and engineering, 2020, 20(26):10635-10641.

[15] Guo Lin , Guo Xiaojing, Wu Binghua ,Yang Po, Kou Yafei, Li Na, Tang Hui. Geo-environmental suitability assessment for tunnel in sub-deep layer in Zhengzhou. European Journal of Remote Sensing, 2020, 1-7.

[16] Peng J, Peng F L. A GIS-based evaluation method of underground space resources for urban spatial planning: Part 1 methodology. Tunnelling and underground space technology. 2018, 74: 82-95.

[17] Peng, Jian, Fang-Le.A GIS-based evaluation method of underground space resources for urban spatial planning: Part 2 application. Tunnelling & Underground Space Technology, 2018, 77: 142-165.

[18] Xiong Yunying, Li Xiaohui, Yuan Feng, Lu Zhitang, Wu Shaoyuan, Dou Fanfan. 3D classification and evaluation of underground space geological environment quality based on SOM and K-means algorithm. Journal of Earth Sciences and Environment,2023,45(04):929-940.

[19] Peng Miaozhi, Wu Jianxiong, Guan Houchun, Qiu Sichen. Geological environment suitability assessment of underground space development in Hefei city. East China Geology, 2021, 42(02):176-184.

[20] DB41/T 2120-2021. Technical specifications for geological environmental suitability evaluation of urban underground space development. Zhengzhou：Henan Province Standard Book Distribution Station,administration for market regulation Henan province,2021.

[21] Zhou C A, Chen C, Ren H. Comprehensive Evaluation on Multiple Constraint Elements of City Underground Space Development and Utilization Based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation Method. Applied Mechanics & Materials, 2013, 357-360: 2754-2758.