19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 1.4.181
DOI: 10.46793/ACUUS2025.1.4.181

RESEARCH ON THE DISTRIBUTION, DEVELOPMENT QUALITY AND DRIVING FORCES FOR THE DEVELOPMENT QUALITY OF URBAN UNDERGROUND SPACE IN CHINA

Jingwei Zhao[1], Yu Sun*[2], Haoqi Li[3], Yinge Zhu[4]

Abstract: As a critical spatial resource for expanding urban land use dimensions, the overall scale of urban underground space has been steadily increasing. Its development quality is influenced by various factors. Based on multi-source data, this study evaluates the development quality of urban underground space in 22 representative Chinese cities using the entropy method across four dimensions: Rari Transit (RT), Underground Space Construction (USC), Underground Space Resilience (USR), and Society Development (SD). Additionally, the PLS-SEM model is employed to analyze the driving forces and their action paths. The findings indicate that: 1) Shenzhen demonstrates the highest development quality in underground space, with underground space resilience (USR) being the most significant dimension affecting its development quality. Economic resilience emerges as the most crucial single indicator; 2) According to the PLS-SEM model, USR exhibits the strongest direct effect and serves as a key mediator. The path " society development(SD) → underground space resilience(USR) → urban underground space development quality(UUSDQ)" shows the most pronounced indirect effect; 3) Based on these results, two strategies are proposed: guiding spatial supply-side reform through social development and enhancing government decision-making efficiency by improving the management mechanism for underground space development. Specific development strategies are also suggested for cities with medium and low-quality underground spaces.

Keywords: Urban underground space, Development quality assessment, Entropy weight method, Driving factors, PLS-SEM modeling

1. INTRODUCTION

The development and utilization of underground space in Chinese cities encompasses a range of functions, including underground parking, commercial facilities, recreational spaces, and metro stations. Over the past 70 years, the construction approach has transitioned from an initial focus on civil air defense projects to one led by rail transit systems, and more recently, to a model guided by pedestrian activity demands. As a critical component of the so-called "fourth territory," urban underground space offers diverse services such as retail, dining, and entertainment(Tang & Tang, 2024). Its forward-looking spatial characteristics have elevated its development to a national strategic priority, positioning it as a key trend in future urban planning(The website of the Chinese government, 2024).

According to the *2024 China Urban Underground Space Development Blue Book*, by the end of 2023, the total built area of urban underground space in China had reached 3,276 billion square meters. The per capita underground construction area increased from 3,49 m^2 in 2022 to 3,6 m^2 in 2023, indicating the vast scale of underground development(Beijing: Strategic Consultation Center et al., 2024). However, with rapid urbanization and the continuous expansion of existing underground infrastructure, available underground space resources are

[1] PhD, Zhao Jingwei, Ph.D. in Geotechnical Engineering, professor, College of Civil Engineering and Architecture, Shandong University of Science and Technology, 579 Qianwan Port Road, Qingdao, China, skd991560@sdust.edu.cn.
[2] MSc, Sun Yu, MSc in Architecture Eng., College of Civil Engineering and Architecture, Shandong University of Science and Technology, 579 Qianwan Port Road, Qingdao, China, skdsunyu@sdust.edu.cn.
[3] MSc, Li Haoqi, MSc in Architecture Eng., College of Civil Engineering and Architecture, Shandong University of Science and Technology, 579 Qianwan Port Road, Qingdao, China, 202482040002@sdust.edu.cn.
[4] PhD, Zhu Yinge, Ph.D. in Geotechnical Engineering, lecturer, College of Civil Engineering and Architecture, Shandong University of Science and Technology, 579 Qianwan Port Road, Qingdao, China, zhuyg0221@sdust.edu.cn.

being rapidly depleted(Wang et al., 2025). Consequently, the quality of underground space development has become increasingly significant. Scholars have conducted extensive empirical studies to identify the driving factors behind urban underground space development from multiple perspectives. For example, Zhao et al. (Zhao et al., 2025)applied a geographical detector method and identified three core indicators—above-ground commercial facility density, underground facility density, and population heat value—that significantly influence the spatial layout of underground commercial areas. Zeng & Chen (Zeng & Chen, 2018) used the length of operational metro lines as a proxy for underground space development intensity and found that cities with high population density and high GDP per unit area tend to develop underground infrastructure more rapidly. Sun et al. (Sun et al., 2018)measured underground development intensity using per-unit-area metrics and employed OLS regression to confirm that development scale is strongly correlated with social indicators such as resident population density, GDP per unit area, and vehicle ownership per hundred residents. Furthermore, Chen et al.(Chen et al., 2021), based on heat map data, demonstrated that population density not only exhibits a strong positive correlation with the morphological distribution and development intensity of underground space but also serves as a predictive factor for future development intensity. These findings collectively indicate that the configuration, form, and evolution of urban underground space are shaped by a multitude of interrelated factors.

Current research on the quality of underground space development primarily focuses on geological environmental conditions(Xiong et al., 2025; Zhang et al., 2023), subsurface resource quality(Guo et al., 2024; Yan et al., 2021), and macro-level governance frameworks(Wang et al., 2019; Yi, 2025). However, during the rapid development of urban underground infrastructure, other multidimensional factors—including policy interventions(Qiao & Peng, 2023), economic drivers(Chen et al., 2018; Yu et al., 2025; Zhao et al., 2025), rail transit expansion(Yu et al., 2025; Zhao et al., 2025), and underground resilience(Li & Wang, 2025; Luo et al., 2023)—also exert significant influence on development quality. Therefore, from a practical application standpoint, there is an urgent need to quantitatively assess the development quality of urban underground space. Additionally, understanding the driving forces across different dimensions and the causal relationships among them remains a critical research gap. To address this, this study employs spatial analysis techniques such as kernel density estimation and spatial autocorrelation to characterize the spatial distribution patterns of urban underground space in China. Subsequently, the entropy method is applied to evaluate the development quality of underground space in 22 selected cities. Finally, the PLS-SEM model is utilized to explore the underlying driving mechanisms and their paths, aiming to provide theoretical insights and practical references for the sustainable development of urban underground space.

2. MATERIAL AND METHODS

2.1. Spatial analysis

This paper visualizes the distribution and characteristics of underground space in Chinese cities using kernel density estimation and spatial autocorrelation methods. Kernel density estimation is a non-parametric statistical method in spatial analysis (Yang & Li, 2021) that describes the distribution pattern of random variables through density functions. The non-discrete continuous density surface generated by this method can simulate the continuity of density(Huang et al., 2023; Yang et al., 2019). In this study, streets are used as the minimum geographical spatial units to aggregate the kernel density values of underground space POIs (Points of Interest) and treat them as observations. Spatial autocorrelation includes global spatial autocorrelation and local spatial autocorrelation. Global spatial autocorrelation measures the clustering or dispersion of attribute values across spatial units within the entire study area, reflecting systematic spatial associations. Local spatial autocorrelation measures the spatial association between the attribute value of a specific spatial unit and its neighboring units(Fan & Myint, 2014; Meng et al., 2005). The calculation formula is as follows:

$$\text{Global Moran's I} = \sum_{i=1}^{m}\sum_{j=1}^{m}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)W_{ij}\Big/ S^2 \sum_{i=1}^{m}\sum_{j=1}^{m} W_{ij} \tag{1}$$

$$\text{Local Moran's I} = \left(x_i - \bar{x}\right)\sum_{j=1}^{m} W_{ij}\left(x_j - \bar{x}\right)\Big/ S^2 \tag{2}$$

In the formula, m represents the number of geographical units involved in the calculation, $\bar{x}$ represents the mean of the observed values (expressed as kernel density), S^2 represents the variance of the observed values, W_{ij} represents the spatial weight between the i -th element and the j -th element, and x_i and x_j respectively represent the observed values of geographical units i and j .

2.2. Entropy method

The entropy method is an objective weighting approach that calculates the information entropy of indicators to reflect the magnitude of their information content. Its core principle is to determine the weight values of each evaluation indicator based on their respective information entropy. The calculation process is as follows:

(1) Standardization processing

Range standardization is applied to render the 15 indicators dimensionless. The calculation formula is as follows:

When the indicator is a positive indicator, positive normalization processing is performed:

$$x_{ij} = \frac{x'_{ij} - \min\left(x'_{ij}\right)}{\max\left(x'_{ij}\right) - \min\left(x'_{ij}\right)} \tag{3}$$

When the indicator is a negative indicator, reverse normalization processing is applied:

$$x_{ij} = \frac{\max\left(x'_{ij}\right) - x'_{ij}}{\max\left(x'_{ij}\right) - \min\left(x'_{ij}\right)} \tag{4}$$

In the formula, x'_{ij} represents the original data of the j-th indicator for the i-th city, and x_{ij} represents the data after standardization processing.

(2) Weight computation

$$P_{ij} = \frac{x^*_{ij}}{\sum_{i=1}^{n} x^*_{ij}} \tag{5}$$

$$d_j = 1 - \left(-K \cdot \sum_{i=1}^{n}\left(P_{ij} \cdot \ln\left(P_{ij}\right)\right)\right) \tag{6}$$

$$W_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{7}$$

In the formula, n denotes the number of cities, m denotes the number of evaluation indicators, P_{ij} denotes the proportion of the j-th indicator for the i-th city in the corresponding indicator, x^*_{ij} denotes the non-negatively shifted data, d_j denotes the information utility value (i.e., redundancy) of the j-th indicator, and W_j denotes the weight coefficient of the j-th indicator.

2.3. Partial Least Squares Structural Equation Modeling (PLS-SEM)

Partial least squares structural equation modeling (PLS-SEM) is a multivariate statistical technique that integrates principal component analysis, canonical correlation analysis, and ordinary least squares regression(Cepeda-Carrion et al., 2019). Unlike traditional methods, PLS-SEM does not require strict assumptions of multivariate normality, enabling researchers to simultaneously examine latent and observed variables. Additionally, it effectively uncovers latent relationships among variables even in the presence of multicollinearity, yielding more robust and reliable results. The PLS-SEM framework comprises two key components: the structural model (inner model), which specifies the relationships among latent variables, and the measurement model (outer model), which assesses the relationships between observed variables and their corresponding latent constructs. The calculation formulas are presented as follows:

$$X = \Lambda_x \xi + \delta \tag{8}$$

$$Y = \Lambda_y \eta + \varepsilon \tag{9}$$

$$\eta = C\eta + \Gamma\xi + \zeta \tag{10}$$

In the equation, X and Y represent exogenous and endogenous indicators, respectively. Λ denotes the relationship between observed variables and latent variables, while δ and ε represent measurement errors. η

refers to an endogenous latent variable, ξ represents an exogenous latent variable, C indicates the influence of exogenous latent variables on endogenous latent variables, Γ reflects the effect of some endogenous latent variables on other endogenous latent variables, and ζ signifies the regression residual (Wang et al., 2022).

3. RESEARCH AREA AND DATA SOURCES

3.1. Research Area and Assessment Framework

To analyze the spatial layout characteristics of urban underground space, this study defines the administrative regions of China as the research scope and employs kernel density estimation to visualize the distribution patterns of underground space points of interest (POIs). When assessing the development quality of urban underground space, it is essential to consider its multidimensional nature, which encompasses rail transit infrastructure, administrative governance, and underground space resilience. Given the current strong reliance on rail transit in underground space development and construction, the selected cities must possess comprehensive datasets for all required evaluation indicators. Considering both data integrity and accessibility, this study selects 22 cities from the 58 Chinese cities that have operational rail transit systems. The selected sample includes 9 super-large cities, 10 large cities, and 3 Type-I medium-sized cities (Table 1), representing three distinct levels of urban scale. These cities were chosen due to their early initiation of underground space development, the existence of formal underground space-related laws and regulations, and the overall suitability of their development contexts for quality evaluation.

Table 1. *Basic information of 22 sample cities.*

The underground space cluster to which it belongs	**City**	**City classification**	**Rail transit mileage (km)**	**Permanent resident population density (persons/km²)**	**Per capita GDP (ten thousand yuan)**
Beijing-Tianjin-Hebei Urban Agglomeration	Beijing	Hyper-city	897	1332	20,02
	Tianjin	Hyper-city	334,92	1140	12,27
	Hebei	Type-I large city	74,28	710	7,29
Shandong Peninsula Urban Agglomeration	Jinan	Megacity	96,7	921	13,52
	Qingdao	Megacity	352,1	918	15,2
Central Plains Urban Agglomeration	Zhengzhou	Megacity	415,55	1719	10,47
	Xian	Megacity	422,21	1295	9,18
Yangtze River Mid-Reach Urban Agglomeration	Wuhan	Hyper-city	518	1622	14,53
	Changsha	Megacity	236,35	898	14,38
Yangtze River Delta Urban Agglomeration	Shanghai	Hyper-city	896	3923	18,98
	Suzhou	Megacity	350	1479	19,03
	Wuxi	Type-I large city	143,93	1619	20,62
	Nanjing	Megacity	484	1449	18,24
	Hangzhou	Hyper-city	516	743	16,02
Chengdu-Chongqing Dual-city Economic Circle	Chengdu	Hyper-city	633,3	1493	10,31
	Chongqing	Hyper-city	575	387	10,09
Guangdong-Hong Kong-Macao Greater Bay Area	Shenzhen	Hyper-city	595,1	8906	19,45
	Guangzhou	Hyper-city	705.1	2532	16,12
	Foshan	Megacity	150	2532	13,81
Guangdong-Fujian-Zhejiang Coastal Urban Agglomeration	Xiamen	Type-I large city	98,4	3135	15,14
Liaozhongnan Urban Agglomeration	Dalian	Megacity	237	599	11,61
	Shenyang	Megacity	188	1799	8,82

Based on existing literature and prior research on urban underground space development, this paper establishes four first-level indicator dimensions: rail transit, underground space construction, underground space resilience, and social development. Rail transit (RT) reflects a city's capacity to integrate rail lines within its underground space, the proportion of public transportation borne by rail transit, and the degree of alignment between rail transit networks and job-residence spatial patterns. Underground space construction (USC) indicates the level of underground development through indicators such as functional diversity, the rate of infrastructure undergroundization, and facility clustering. Underground space resilience (USR) measures the system's adaptability in policy, economic, and institutional dimensions, using indicators including the number of relevant laws and regulations, GDP per unit area of underground space, and the proportion of investment in science, technology, and education relative to GDP. Social development (SD) captures foundational driving factors for high-quality underground space development, including demand for underground space utilization, economic feasibility, and overall societal development levels. A total of 15 indicators were selected to construct the evaluation framework for urban underground space development quality (Table 2).

Table 2. *Evaluation Framework for Urban Underground Space Development Quality*.

Overall Goal	**First-Level Indicators**	**Second-Level Indicators**	**Indicator Description**	**Weight (%)**	**Indicator Attribute**
Urban Underground Space Development Quality (UUSDQ)	Rari Transit (RT)	Integration degree	Average Integration Degree of Rail Transit Lines	3,75	+
		Orbital coverage	Proportion of 800-Meter Rail Transit Coverage for Commuting	4,37	+
		Rail transit passenger share	Rail Transit Passenger Volume as a Share of Total Public Transport Volume	3,66	+
		Commuting accessibility	Proportion of Rail Transit Service Capacity within a 45-Minute Travel Time	2,66	+
	Underground Space Construction (USC)	Static transportation infrastructure	Underground Parking Lot Ratio (Share of Total Parking Lots)	5,48	+
		Underground facility utilization rate	Urban Underground Space POI Density Ratio (Share of Total POIs)	8,09	+
		Functional diversity index	Functional Diversity Index of Underground Facilities in Urban Built-Up Areas	3,06	+
		Underground facility agglomeration level	Optimal Agglomeration Scale from Multi-Distance Spatial Clustering Analysis	6,53	+
	Underground Space Resilience (USR)	Policy resilience	Number of Enacted Laws and Regulations on Underground Space	7,19	+
		Economic resilience	GDP per Unit Administrative Area	17,00	+
		Institutional and organizational resilience	Scientific Research and Education Investment as a Share of Regional GDP	9,48	+
	Society Development (SD)	Population density	Population Density Based on Permanent Residents and Urban Administrative Area	13,48	+
		Nighttime light intensity	Annual Average Nighttime Light Intensity	5,04	+
		Economic development level	Per Capita Regional GDP (Regional GDP Divided by Permanent Resident Population)	5,26	+
		Urbanization rate	Urban Population Proportion in Total Population	4,95	+

3.2. Data Source

The vector map of urban administrative districts was obtained from Tianditu (www.tianditu.gov.cn); road network data were sourced from OpenStreetMap (www.openstreetmap.org); rail transit commuting proportions and related data were derived from the Commuting Monitoring Report of Major Chinese Cities; per capita GDP, legal regulations, and other relevant data were collected from municipal statistical yearbooks and official government websites; nighttime light data were provided by the Earth Observation Group (https://payneinstitute.mines.edu/eog/); POI (Point of Interest) and additional datasets were extracted from Amaps (www.amap.com). All data are valid as of April 2025.

4. RESULTS

4.1. Spatial Analysis Results

4.1.1. Urban underground space development in China exhibits a spatial pattern characterized by "four centers, four clusters, three axes, and multiple points".

Currently, the development pattern of urban underground space in China exhibits a structure characterized as "four centers, four clusters, three axes, and multiple points." Along the three major urban development axes—coastal regions, the Yangtze River corridor, and the Beijing-Guangzhou line—four key underground space development centers have emerged: the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration, the Guangdong-Hong Kong-Macao Greater Bay Area, and the Chengdu-Chongqing dual-city urban agglomeration. These regions represent critical zones for realizing compact and intensive development through functional integration and three-dimensional urban planning in the new era. Moreover, they constitute the leading force driving high-quality underground space development nationwide. In addition, various underground space development clusters have formed around central cities of different scales, including the coastal urban agglomerations of Guangdong-Fujian-Zhejiang, the Shandong Peninsula urban agglomeration, the Central Plains urban agglomeration, and the Yangtze River Mid-reach urban agglomeration. In these areas, underground space development is notably more advanced in the core cities of each urban cluster. Furthermore, in provinces such as Liaoning, Guizhou, and Guangxi, as underground space utilization expands in both scale and sophistication, distinct regional nodes with significant development have gradually taken shape.

Kernel density analysis of underground facility POIs at a clustering scale of 28 km reveals that most regions exhibit relatively low kernel density values, generally below 0,101. The range of high-density areas falls between 2,22 and 25,716, highlighting substantial disparities in the extent of underground space development and utilization across cities. Spatially, the concentration of underground facilities declines progressively from the eastern coastal regions toward the central and western parts of the country. Provincial capitals and administrative centers demonstrate higher levels of clustering compared to other cities. Moreover, cities with well-developed underground infrastructure exert a radiating influence on surrounding areas. For example, large-scale underground space development centers have formed in metropolitan regions such as the Yangtze River Delta and the Beijing-Tianjin-Hebei urban agglomeration. In contrast, regions in western and northern China—including Xinjiang, Tibet, Qinghai, and Inner Mongolia—show relatively limited underground space development, with facilities remaining spatially fragmented and dispersed (Figure 1).

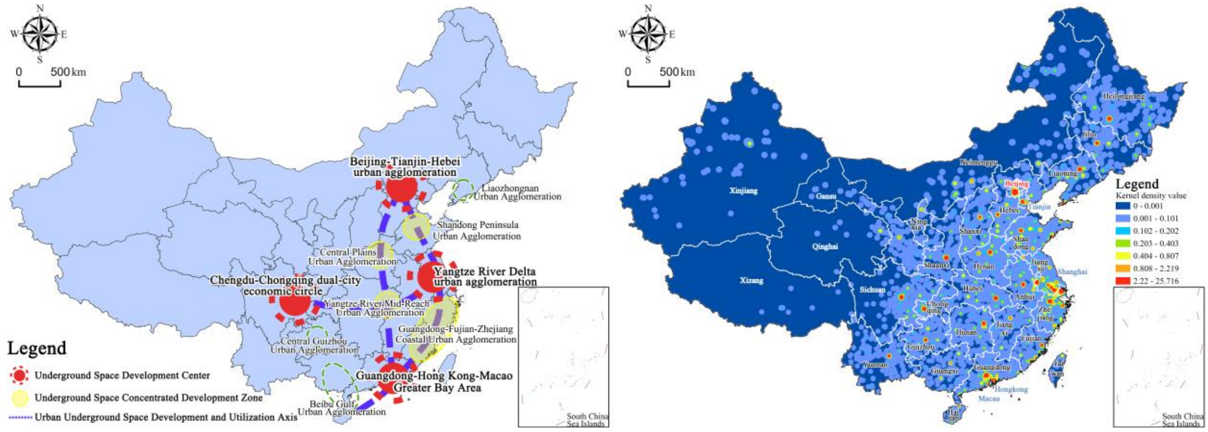

Figure 1. *Development Patterns and Spatial Layout Characteristics of Urban Underground Space in China*.

The development and construction costs of urban underground space are approximately two to three times higher than those of surface buildings, necessitating substantial financial investment and advanced technological support. Among various underground facilities, the underground rail transit system occupies a central position due to its strong capacity for alleviating urban traffic congestion, efficient use of land resources, and critical role in advancing sustainable urban development. A superimposed analysis of nuclear density, metro lines, and GDP data for underground space facilities in major Chinese cities reveals a high degree of spatial consistency between underground infrastructure distribution and metro line layouts. This indicates that the planning and layout of underground rail transit systems significantly influence the spatial distribution of underground facilities. Furthermore, the spatial pattern of underground space facilities demonstrates a concentric decline from the city center outward, closely reflecting the agglomeration characteristics of urban economic activities and the spatial structure of urban development. There is also a clear positive correlation between urban GDP levels and the density of underground space facilities—cities with stronger economies can afford higher development costs and adopt more advanced technologies, resulting in a more concentrated and extensive underground facility network (Figure 2).

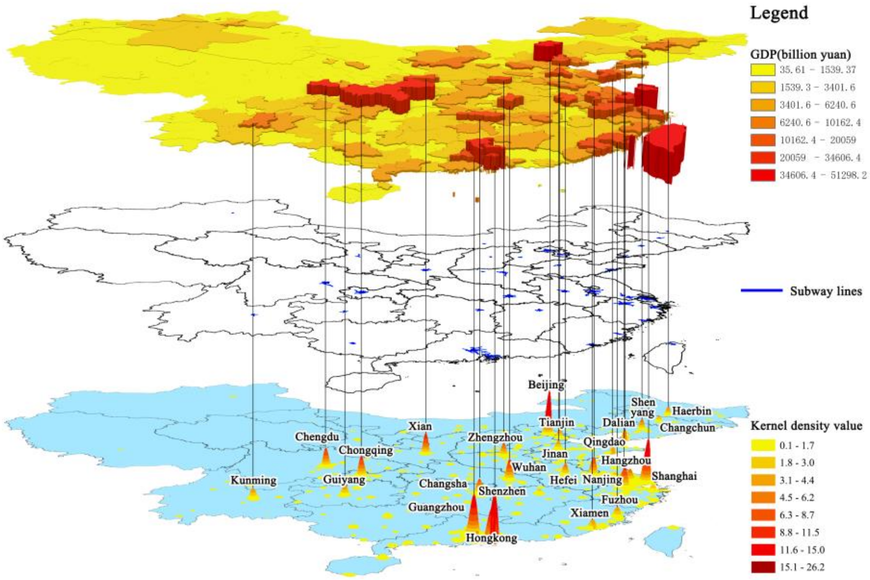

Figure 2. *Overlay Analysis of Underground Space Agglomeration, Subway Networks, and GDP.*

4.1.2. The development centers of urban underground space exhibit significant agglomeration characteristics.

Urban underground facilities were aggregated at the street level as the basic spatial unit for nuclear density calculation, followed by spatial autocorrelation analysis. The global Moran’s Index ranges from -1 to 1, where an absolute value closer to 1 indicates stronger spatial correlation within the system. A positive value reflects positive spatial autocorrelation, while a negative value suggests negative autocorrelation. The results show that the global Moran’s Index for urban underground space in China is 0,301, with a Z-score of 176,645 and a statistically significant p-value of 0,000. This confirms the presence of significant positive spatial agglomeration in the distribution of underground space across Chinese cities.

According to the local Moran's Index (Figure 3), high – high clustering types are relatively rare, whereas low – low clustering dominates the spatial pattern. However, small-scale high – high clusters have formed around each "underground space development center," surrounded by larger low – high clustering zones. As shown in the local Moran's scatter plot (Figure 4), although the number of low – low clusters (3.384) far exceeds that of high – high clusters （635）, the low – low clusters in the third quadrant are distributed closer to the origin, indicating both the cluster and its neighboring areas exhibit nuclear density values significantly below the average. This implies weak spatial autocorrelation among low-density regions—despite their wide distribution, these areas remain scattered and do not form strong spatial agglomeration. In contrast, high – high clusters in the first quadrant are more widely dispersed with higher local Moran's Index values. These clusters, concentrated around the “underground space development centers,” not only exhibit higher internal density but also effectively stimulate the development of surrounding underground infrastructure, leading to the formation of multiple low – high clustering development belts. This further demonstrates stronger spatial autocorrelation among high – high clustering areas.

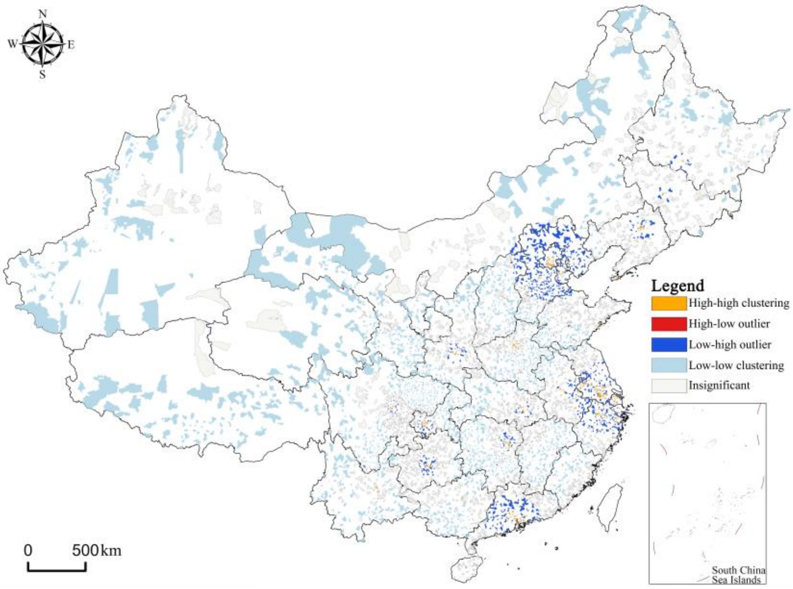

Figure 3. *The results of the local Moran's I.*

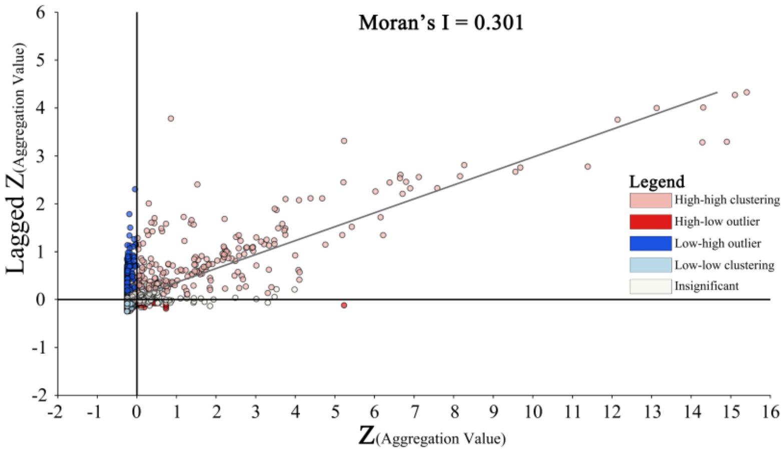

Figure 4. *Scatter plot of local Moran's I.*

4.2. Assessment of Development Quality

4.2.1. Classification of Evaluation Outcomes

The UUSDQ was assessed across 22 cities (Figure 5). Among them, Shenzhen achieved the highest score of 0,748, while Shijiazhuang scored the lowest at 0,143. The average development quality index was 0,334, with a difference of more than 0,605 between the highest and lowest scores, indicating substantial inter-city disparities in underground space development quality. To better reflect these differences, the comprehensive evaluation scores were categorized using one standard deviation as the classification criterion. Accordingly, the UUSDQ was classified into four levels: high (0,469–0,748), relatively high (0,334–0,469), medium (0,197–0,334), and relatively low (0–0,197). Analysis reveals that Shenzhen and Shanghai fall into the high-quality category; seven cities, including Beijing and Guangzhou, are classified as relatively high quality; eleven cities, such as Xi’an and Wuxi, fall into the medium-quality group; and Dalian and Jinan are categorized as having relatively low development quality.

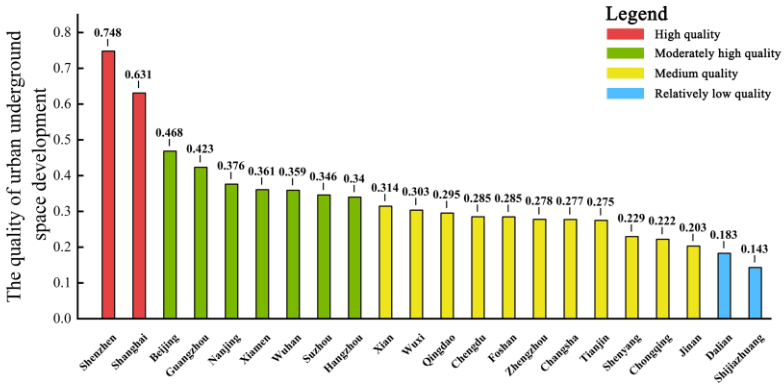

Figure 5. *Assessment Results of Urban Underground Space Development Quality.*

4.2.2. Analysis of Weighting Factors

As illustrated by the index weights and evaluation scores across each dimension (Figure 6), among the first-level indicators, USR (33,67%) and SD (28,73%) carry the highest weights, and their respective scores contribute significantly to the overall evaluation score. These two dimensions thus represent the most influential factors in determining the quality of urban underground space development. Within the SD dimension, permanent resident population density and urbanization rate reflect the actual demand for underground space development, whereas per capita GDP and nighttime light intensity directly indicate a city's investment capacity and economic strength in this domain. Consequently, the SD dimension holds a substantial weight in the overall assessment. In the USR dimension, laws and regulations, GDP per unit area, and the proportion of investment in scientific research and education exert significant influence across multiple stages, including planning approaches, construction scope, and developmental direction.

Among the second-level indicators, economic resilience within the USR dimension and population density within the social development dimension exhibit the highest individual weights, at 17,00% and 13,48%, respectively.

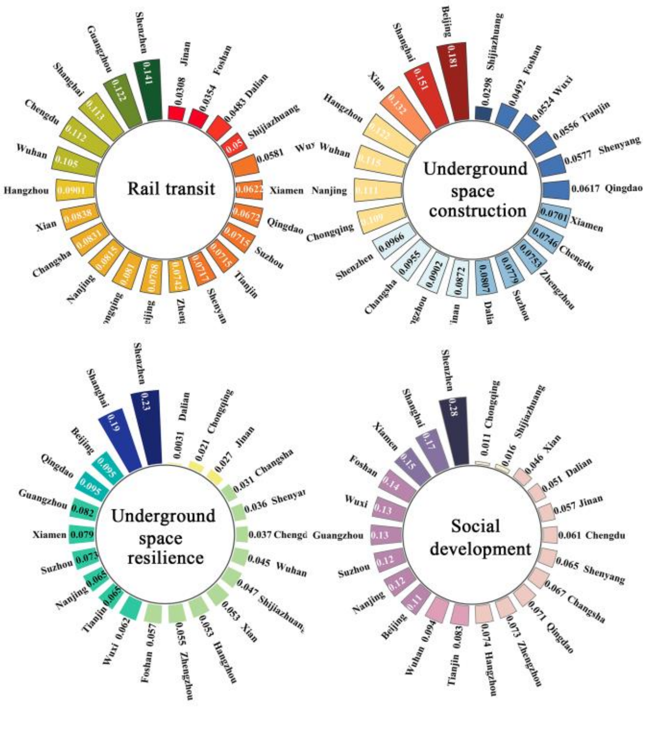

Figure 6. *First-Level Indicator Scores for Urban Underground Space Development Quality.*

4.3. Driving Force Analysis Using the PLS-SEM Model

4.3.1. PLS-SEM Model Development

Although the comprehensive evaluation based on the entropy method revealed differences in UUSDQ scores among cities and highlighted the contribution of key indicators, the use of static weights limited the ability to interpret the dynamic interactions among dimensions. Therefore, this study further employed PLS-SEM to investigate the mechanisms and internal influence paths of each indicator on urban underground space development quality. Data were imported into SmartPLS 4 software, with RT, USC, USR, and SD defined as latent variables and the 15 second-level indicators serving as observed variables. After processing through the PLS-SEM algorithm, the observed variable "policy resilience," which exhibited a negative outer loading, was removed, leading to the construction of the final PLS-SEM model for underground space development quality.

The significance of the model paths and potential multicollinearity were assessed using the bootstrap method (5.000 resamples) and variance inflation factor (VIF) values, respectively. The results indicated that the highest VIF value across all observed variables was 3,445, suggesting no significant multicollinearity issues within the dataset. In the structural model, all path coefficients between latent variables showed p-values less than 0,05, confirming statistical significance (Table 3).

Table 3. *Path Analysis of the PLS-SEM Model.*

Path	Original sample	Standard deviation	T statistics	P value
USC→UUSDQ	0,221	0,109	2,020	0,043*
USR→UUSDQ	0,431	0,128	3,358	0,001***
SD→UUSDQ	0,362	0,112	3,222	0,001***
RT→UUSDQ	0,190	0,087	2,186	0,029*
SD→USR	0,818	0,039	21,011	0,000***
RT→USC	0,555	0,096	5,791	0,000***

Note: $^{*}p<0{,}05$, $^{***}p<0{,}001$

4.3.2. Results and Analysis of Model Operation

In the PLS-SEM model results, the path values between observed variables and latent variables represent the factor loadings of the observed variables, where the magnitude indicates their explanatory power on the corresponding latent variables. The path values between latent variables are referred to as path coefficients (β), which reflect the strength of the causal relationships among latent variables. The values within the circles associated with each latent variable represent the coefficient of determination (R^2), indicating the proportion of variance in a given latent variable explained by other latent variables in the model. A higher R^2 value suggests stronger explanatory and predictive power of the model (Figure 7). Specifically, the R^2 value for the latent variable "UUSDQ" is 0,984, meaning that RT, USC, USR, and SD collectively explain 98,4% of its variance, demonstrating that the model has strong explanatory capability.

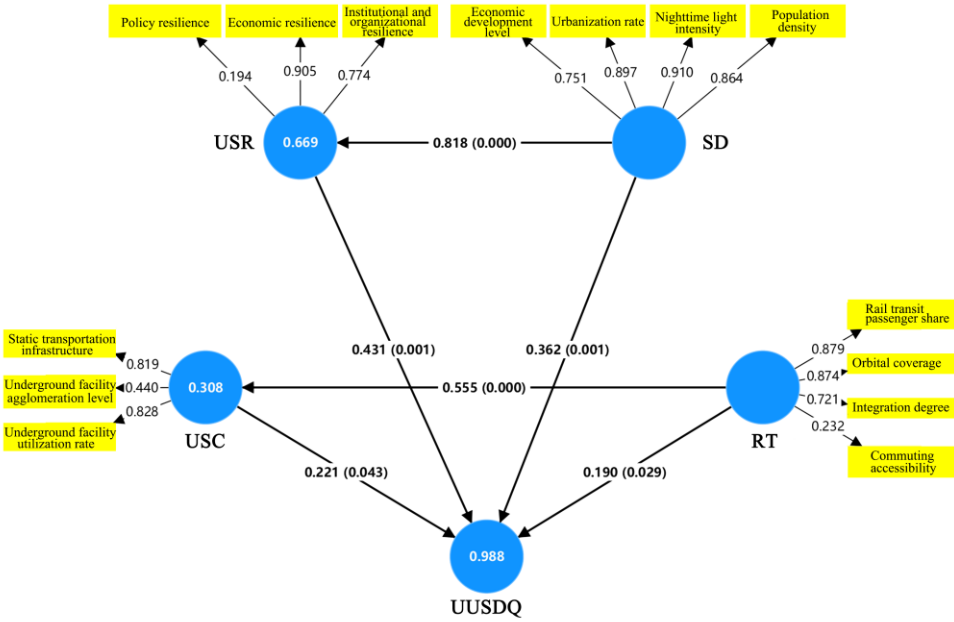

Figure 7. *Results of the PLS-SEM Model Operation.*

All four dimensions exert a significant positive driving effect on the UUSDQ. Among the direct effect paths influencing this development quality, USR demonstrates the strongest impact (β = 0,431). The legal framework governing underground space, per capita GDP, and the proportion of investment in science, technology, and education directly enhance the stability of underground resilience from policy, economic, and institutional perspectives, thereby influencing the overall development quality of urban underground space. Thus, USR serves as the key driving force. Additionally, SD also exerts a relatively strong influence (β = 0,329). Indicators such as per capita GDP, urbanization rate, nighttime light intensity, and permanent resident population density are closely associated with the economic capacity for investment and the demand for underground space, making them important determinants of UUSDQ.

Among all direct effect paths, the path coefficient between SD and USR is the highest (β = 0,818), indicating a highly significant positive relationship. The comprehensive development level of cities or regions significantly enhances the risk response capability of underground space systems—such as their ability to cope with disasters and resource shortages. In other words, the accumulation of social resources strongly supports the systematic construction of underground space. Infrastructure investment and facility undergroundization driven by SD directly reinforce the resilience of underground space, highlighting its role as a critical driver. Moreover, the path coefficient for "RT → USC" is also substantial (β = 0,555), suggesting a significant positive correlation. The completeness and operational efficiency of urban rail transit systems strongly promote the efficiency of underground space development, reflecting a high degree of synergy between transportation infrastructure and underground space utilization.

Among the indirect effect paths, only the path "SD → USR → UUSDQ" has a statistically significant P value (0,002), with an indirect effect of 0.352. Notably, the direct effect of SD on USR (β = 0,818) is significantly stronger than that of USR on UUSDQ (β = 0,431), indicating that SD constitutes a more fundamental driving factor. According to the mediation effect test method(Wen et al., 2004), USR functions as a mediator within this path. This implies that SD not only directly influences the UUSDQ but also indirectly affects it through the mediating variable of USR.

5. DISCUSSION

5.1. Discussion on Spatial Analysis

The overall density of underground space in Chinese cities remains relatively low, and its spatial distribution exhibits a clear "core-periphery" pattern. In major development centers such as the Beijing-Tianjin-Hebei region and the Yangtze River Delta, underground space density is significantly higher, displaying a high-high clustering pattern. These regions not only serve as China's key economic growth poles but also feature high GDP levels and population densities, which provide a solid economic foundation and strong market demand for underground space development. In concentrated development zones and key nodes—such as the Shandong Peninsula urban agglomeration (Jinan, Qingdao), the Central Yangtze River urban agglomeration (Wuhan, Changsha), and the Liaozhongnan urban agglomeration (Shenyang)—underground space development primarily depends on provincial capitals, administrative centers, and prefectural-level cities, leading to the formation of smaller-scale underground clusters. Collectively, these areas constitute the "core areas" of urban underground space in China.

In contrast, the "peripheral areas" surrounding the core regions exhibit lower underground space density, predominantly characterized by low-low clustering. Moreover, the development cost of underground space is relatively high, and its utilization heavily relies on surface infrastructure and urban development. Consequently, despite the large number of low-low clustered zones in these peripheral regions, systematic underground clusters and interconnected networks have yet to emerge due to limitations in development maturity and regional economic capacity. At present, China's macro-level policies on underground space prioritize the advancement of regions with existing advantages in this domain. The focus of underground facility construction lies in comprehensive utility tunnels (The State Council of the People's Republic of China, 2024) and consumption-oriented facilities(The State Council of the People's Republic of China, 2025), further enhancing the development level and spatial concentration of underground space in the core areas.

5.2. Discussion on Development Quality Assessment

The evaluation system assesses the quality of urban underground space development by integrating the actual usage efficiency of underground facilities with the level of social development. For example, the indicator "railway coverage" is defined as the proportion of commuting population in central urban areas whose residences and workplaces are both located within 800 meters of a rail transit station. Similarly, the "institutional and organizational resilience" indicator under the underground space resilience dimension is measured by the proportion of investment in science, technology, and education relative to regional GDP. These indicators strictly follow the established criteria for constructing the urban underground space development quality index. Within each of the four quality tiers, spatial disparities among cities are relatively small; however, the gap between the high-quality tier and the relatively high-quality tier is substantial.

Among high-quality cities, Shenzhen demonstrates outstanding performance across RT, USR, and SD dimensions, while Shanghai also ranks highly across all indicators. As a result, both cities are classified as high-quality and significantly outperform other megacities and large cities such as Shijiazhuang and Jinan. In the relatively high-quality group, the overall development quality is constrained by low scores in specific dimensions. For instance, Suzhou ranks 13th in USR, and Xiamen ranks 17th in RT performance. In medium- and lower-quality cities, most indicators score at or below average levels, resulting in an overall lower development quality. Nevertheless, some cities exhibit strengths in certain dimensions—for example, Qingdao ranks 4th in USR, and Suzhou ranks 5th in SD.

According to the entropy method, higher indicator weights indicate greater informational content (Luo et al., 2023), which reflects larger inter-city differences in underground space development quality. USR and SD carry the highest weights at 33,67% and 28,73%, respectively. Economic resilience and population factors rank first and second among individual indicators, with weights of 17,00% and 13,48%. Considering the meanings of these two factors, Shenzhen and Shanghai had population densities of 8.906 people/km^2 and 3.923 people/km^2, respectively, and economic resilience values of 17,32 billion yuan/km^2 and 7,44 billion yuan/km^2 by the end of 2024. These figures highlight the significantly higher demand for underground space and stronger regional economic support capabilities in these two cities compared to others, contributing to their superior performance on key indicators.

5.3. Discussion on Driving Forces and Mechanisms

The PLS-SEM model reveals that underground space resilience exerts the strongest direct positive influence on the quality of underground space development among all latent variables. This finding aligns with its corresponding maximum weight value in the evaluation system. As reflected by its observed indicators, underground space resilience primarily captures the system’s capacity to respond to risks and the ability of local governments to provide administrative guidance and intervention in the planning, construction, and management of underground space. Given the highly irreversible nature of underground development, enhanced resilience, forward-looking planning, and supportive legal frameworks are essential for promoting sustainable and healthy development. Therefore, underground space resilience influences development quality through multiple dimensions, including risk mitigation, technological advancement, and strategic planning.

In terms of direct effects, SD demonstrates the most substantial impact on underground space resilience, with a path coefficient of 0,818. This indicates a strong positive relationship between SD and USR. The observed variables associated with this latent construct reflect fundamental factors such as underground space demand, urban supply capacity, and the extent of infrastructure undergroundization. These factors not only directly shape the overall quality of underground space development from a supply-demand perspective but also rely on underground space resilience as a mediating mechanism to amplify their positive influence. Specifically, the indirect effect path—SD → USR → UUSDQ—demonstrates that SD can drive improvements in underground space quality at a foundational level. The resulting demand and construction activities necessitate both proactive and effective governance from local authorities, as well as the mediating role of underground space resilience.

6. CONCLUSION

This study selected 15 evaluation indicators and applied a combined weighting method to assess the quality of underground space development across 22 Chinese cities. The assessment was conducted from four dimensions: RT, USC, USR, and SD. Furthermore, the PLS-SEM model was employed to explore the driving forces and their underlying paths influencing urban underground space development quality. The following conclusions were drawn:

(1) The spatial distribution of underground space in Chinese cities exhibits an overall pattern characterized as "four centers, four clusters, three axes, and multiple points." The degree of agglomeration is higher in eastern coastal regions compared to central and western regions, and provincial capitals and municipalities show greater facility concentration than other cities. A significant positive spatial autocorrelation exists in the distribution of underground space. While low-low clustering areas are more widespread, high-high clustering areas are concentrated around key development centers and clustered zones.

(2) Shenzhen achieves the highest score (0,748) for UUSDQ and outperforms other cities in RT, USR, and SD. Although inter-city differences within each quality tier are relatively small, substantial gaps exist between tiers. In the evaluation system, USR is identified as the most influential dimension, with a weight of 33,67%. Economic resilience ranks as the most impactful single indicator, carrying a weight of 17,00%.

(3) RT, USC, USR, and SD all exert positive driving effects on underground space quality. Among these, USR demonstrates the strongest direct effect, with a path coefficient of 0.431. Moreover, it plays a mediating role in the indirect path “SD → USR → UUSDQ,” which has an indirect effect coefficient of 0.352. This provides a novel causal explanation for the determinants of underground space quality.

(4) To enhance underground space development, it is essential to improve management mechanisms and increase government decision-making efficiency, guided by social development-led supply-side reforms. Coordination among planning, administrative approval, and regulatory departments should be strengthened to optimize a government-led, multi-stakeholder public service delivery model that integrates market and social resources. Increasing investment in science, technology, and education can facilitate the transformation of research outcomes into improvements in underground space quality. Additionally, development strategies should prioritize people’s needs, allocating underground functions based on population density gradients. In highly urbanized cities, integrating underground space into 15-minute living circle standards or broader regional frameworks can promote the equitable expansion of underground infrastructure.

(5) Cities with high-quality underground space development should consolidate existing strengths while addressing weaker dimensions to achieve comprehensive improvement. For instance, Suzhou and Xiamen exhibit relatively low integration and commuting coverage levels within their tier and should focus on enhancing rail transit efficiency and strengthening its support for residential and employment spaces. Xi’an and Hangzhou could establish dedicated underground space R&D funds to accelerate the industrialization of patented technologies, thereby transforming regional economic innovation into enhanced underground resilience.

(6) For cities with medium- and low-quality development, it is crucial to identify both advantages and weaknesses and implement targeted interventions. Qingdao, despite having a robust legal framework for underground space, suffers from low rail line integration and limited underground facilities. Therefore, constructing commercial and cultural complexes centered on transportation hubs, linking fragmented rail lines, and developing integrated mountain-sea-city transfer systems are recommended. Tianjin demonstrates strong scientific investment (3.33%) and high urbanization rates (>85%), but lags in underground parking and facility penetration. Enhancing vertical development in high-density zones and establishing functional coupling mechanisms across vertical layers can help address this imbalance. Chongqing shows moderate rail transit coverage (20% for commuting populations) but lacks sufficient legal frameworks and economic strength. Strengthening its economic foundation and configuring underground facilities according to population density and development intensity gradients, along with incorporating underground planning into general urban plans, would support sustainable growth.

All 22 cities analyzed in this study have rail transit coverage. During indicator selection and PLS-SEM model construction, rail transit factors were adequately considered. When applying this model to cities without rail transit or expanding the scope of analysis, alternative data sources such as bus card swiping records or ride-hailing GPS density within underground facility coverage areas can be used to maintain model applicability across diverse regions.

7. FUNDING

This research was funded by the Qingdao Philosophy and Social Sciences Planning Project (QDSKL2401105), and the Qingdao Double Hundred Research Project (2024-B-136).

8. REFERENCES

[1] Cepeda-Carrion, G., Cegarra-Navarro, J.-G., & Cillo, V. (2019). Tips to use partial least squares structural equation modelling (PLS-SEM) in knowledge management. *Journal of Knowledge Management*, *23*(1), 67–89. https://doi.org/10.1108/JKM-05-2018-0322.

[2] Chen, Y., Zhao, Z., Guo, D., Zou, D., & Chen, Z. (2021). Research on the Correlation between Urban Underground Space and Population Distribution. *Chinese Journal of Underground Space and Engineering*, *17*(3), 637–648(in Chinese).

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

[4] Fan, C., & Myint, S. (2014). A comparison of spatial autocorrelation indices and landscape metrics in measuring urban landscape fragmentation. *Landscape and Urban Planning*, *121*, 117–128. https://doi.org/10.1016/j.landurbplan.2013.10.002.

[5] Guo, J., Liu, K., & Ma, Y. (2024). A methodology for comprehensive quality evaluation of underground space. *Acta Geologica Sinica - English Edition*, *98*(6), 1637–1648. https://doi.org/10.1111/1755-6724.15147.

[6] Huang, J., Lu, H., Jin, H., & Zhang, L. (2023). Urban resilience in China's eight urban agglomerations: Evolution trends and driving factors. *Environmental Science and Pollution Research*, *32*(6), 3072–3098. https://doi.org/10.1007/s11356-023-30971-1.

[7] Li, C., & Wang, Y. (2025). Evaluation of the underground space safety resilience of chinese urban agglomerations based on the "stress-state-response":a case study of underground rail transit in 26 cities. *Journal of Safety Science and Resilience*, S266644962500026X. https://doi.org/10.1016/j.jnlssr.2025.02.001.

[8] Luo, B., Peng, F., Liu, S., & Dong, Y. (2023). Evaluation indicators and models of urban underground space resilience. *Journal of Railway Science and Engineering*, *20*(9), 3570–3578. https://doi.org/10.19713/j.cnki.43-1423/u.t20221866(in Chinese).

[9] Meng, B., Wang, J., Zhang, W., & Liu, X. (2005). Evaluation of Regional Disparity in China Based on Spatial Analysis. *SCIENTIA GEOGRAPHICA SINICA*, *25*(4). https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFQ&dbname=CJFD2005&filename=DLKX200504001(in Chinese).

[10] Qian Qihu, Chen Xiangsheng, Chen Zhilong, et al. 2024 Blue Book on the Development of Urban Underground Space in China [R]. Beijing: Strategic Consultation Center, Chinese Academy of Engineering; Underground Space Branch, Chinese Society for Rock Mechanics and Engineering; Urban Planning Society of China, 2024. (in Chinese).

[11] Qiao, Y., & Peng, F. (2023). Advances and Development Thoughts on Three-Dimensional Urban Underground Cadastre. *Chinese Journal of Underground Space and Engineering*, *19*(2), 359–367, 409(in Chinese).

[12] Sun, L., Li, X., Zhou, D., Wang, W., & Liu, C. (2018). Study on the Correlation between Underground Space Development and Socio-economic Factors. *Chinese Journal of Underground Space and Engineering*, *14*(4), 859–868, 880(in Chinese).

[13] Tang, Y., & Tang, Y. (2024). Analysis of the spatial characteristics and driving forces of underground consumer service space in chinese megacities based on multi-source data. *Sustainable Cities and Society*, *116*, 105924. https://doi.org/10.1016/j.scs.2024.105924.

[14] The State Council of the People's Republic of China. Guidance on Exploring and Promoting the Development and Utilization of Urban Underground Space (No. 146 of 2024 issued by the Ministry of Natural Resources) [EB/OL]. (2024-07-31) [2025-06-01]. Https://www.gov.cn/zhengce/zhengceku/202409/content_6974170.htm(in Chinese).

[15] The State Council of the People's Republic of China. Notice on Carrying out the 2025 Central Government Financial Support for Urban Renewal Actions (Cai Ban Jian [2025] No. 11) [EB/OL]. (2025-04-03) [2025-06-01]. Https://www.gov.cn/zhengce/zhengceku/202504/content_7017720.htm(in Chinese).

[16] The website of the Chinese government. Opinions on Promoting the Innovative Development of Future Industries by Seven Departments Including the Ministry of Industry and Information Technology (MIIT Joint Science and Technology [2024] No. 12) [EB/OL]. (2024-01-18) [2025-01-25]. Https://www.gov.cnzhengcezhengceku202401content_6929021.htm(in Chinese).

[17] Wang, C., Ma, L., Zhang, Y., Chen, N., & Wang, W. (2022). Spatiotemporal dynamics of wetlands and their driving factors based on PLS-SEM: a case study in wuhan. *Science of the Total Environment*, *806*, 151310. https://doi.org/10.1016/j.scitotenv.2021.151310.

[18] Wang, C., Zhou, C., Peng, J., Fan, J., Zhu, H., Li, X., Cheng, G., Dai, C., & Xu, N. (2019). A discussion on high-quality development and sustainable utilization of China's urban underground space in the new era. *Earth Science Frontiers*, *26*(3), 1–8. https://doi.org/10.13745/j.esf.sf.2018.9.2(in Chinese).

[19] Wang, H., Guo, D., Wei, L., Su, J., Zhao, H., & Zhao, X. (2025). Synergistic priority utilization of multiple underground resources: Concept, methods, and application. *Tunnelling and Underground Space Technology*, *162*, 106642. https://doi.org/10.1016/j.tust.2025.106642.

[20] Wen, Z., Zhang, L., Hou, T., & Liu, H. (2004). TESTING AND APPLICATION OF THE MEDIATING EFFECTS. *Acta Psychologica Sinica*, *36*(5), 614–620(in Chinese).

[21] Xiong, Y., Li, X., Yuan, F., Lu, Z., Wu, S., & Dou, F. (2025). 3D evaluation of geological environment quality in underground space based on clustering ensemble. *JOURNALOF HEFEIUNIVERSITY OFTECHNOLOGY (NATURALSCIENCE)*, *48*(1), 78–84, 91(in Chinese).

[22] Yan, J., Zhao, Y., Wang, Z., Wang, Liu, K., Ren, T., & Xu, B. (2021). Comprehensive quality evaluation of underground space resources in Yinchuan City. *GEOLOGICAL BULLETIN OF CHINA*, *40*(10), 1636–1643(in Chinese).

[23] Yang, Y., & Li, Q. (2021). Distribution Pattern and Its Formation Mechanism of Public Recreational Space Based on Pol Data: A Case Study of the Main Urban Area of changsha City. *Modern Urban Research*, *3*, 91–97. https://doi.org/10.3969/j.issn.1009-6000.2021.03.013(in Chinese).

[24] Yang, Z., He, X., Sui, X., & Zhang, J. (2019). Analysis of the Evolution of Urban Center Space Based on POI: A Case Study of Main Area in Kunming. *URBAN DEVELOPMENT STUDIES*, *26*(2), 31–35(in Chinese).

[25] Yi, R. (2025). Scientific development and utilization of underground space resources to stimulate high-quality urban economic development. *Bulletin of Chinese Academy of Sciences*, *40*(4), 725–729. https://doi.org/10.16418/j.issn.1000-3045.20250108001(in Chinese).

[26] Yu, H., Chen, Z., Hu, W., Zhang, J., Xu, C., & Hu, B. (2025). Urban underground space value assessment and regeneration strategies in symbiosis with the urban block: A case study of large residential areas in beijing. *Tunnelling and Underground Space Technology*, *163*, 106728. https://doi.org/10.1016/j.tust.2025.106728.

[27] Zeng, C., & Chen, W. (2018). A Forecasting Model of Urban Underground Space Development Intensity. *Chinese Journal of Underground Space and Engineering*, *14*(5), 1154–1160(in Chinese).

[28] Zhang, P., Zhao, Q., Zhao, L., Liu, J., & Bai, Z. (2023). Evaluation of Geological Environment Quality of Underground Space in Different Layers in Western Zhengzhou. *Chinese Journal of Underground Space and Engineering*, *19*(S2), 510–518(in Chinese).

[29] Zhao, J., Wang, H., Sun, Y., Li, H., & Zhu, Y. (2025). Investigation into the distribution features and determinants of underground commercial spaces in qingdao city. *Buildings*, *15*(10), 1743. https://doi.org/10.3390/buildings15101743.