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Comprehensive Management Strategy of Underground Space Development in China

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Abstract: There is a strong demand for underground space development in China. Underground space utilization is characterized by intense construction difficulty, a long construction period, high costs, and complex social impacts. However, a systematic and reliable management system for underground space development has not yet been established. Therefore, there is an urgent need to conduct strategic studies on the comprehensive management of underground space development from both theoretical and practical perspectives. In this paper's analysis of the current underground space development situation in China, problems in the comprehensive management of underground space are discussed from the aspects of laws and regulations, high-level design, management systems, geological surveys, equipment, information resources, the degree of utilization of intelligence technologies, and comprehensive benefits. Furthermore, a development strategy and countermeasures for underground space development in China are proposed. Considering the long-term strategic objectives and development principles, main tasks earmarked for the future include the establishment of a comprehensive management system, the expansion of management capacity, the intelligentization of space management, and the reinforcement of emergency response safety management. Specifically, a national unified coordination system needs to be established for comprehensive underground space management; relevant laws and regulations, standards, and regulatory evaluation systems should be improved; technologies and professionals are crucial to and should be encouraged in the interest of key equipment development; and urban underground space surveys and information management should be promoted.
Keywords: underground space; development and utilization; comprehensive management; intelligentization; resource survey

1 Introduction

In the *Decision of the CPC Central Committee on Several Major Issues of Comprehensively Deepening Reform* adopted at the Third Plenary Session of the 18th CPC Central Committee, the concept of state governance was proposed at the national level for the first time as an overall goal guiding reforms in all fields. Consequently, urban governance has been identified as an important part of social governance, carving out a direction for the modernization of Chinese cities. The comprehensive management of underground spaces is a major component of urban governance. Focusing on cities' underground space [1], it combines professional management with unified management through administrative, legal, technical, and economic means and the application of cutting-edge technologies such as big data, artificial intelligence (AI), and cloud computing to decision-making. The entire process of underground space planning, design, construction, operation, and maintenance should be coordinated and controlled, with the ultimate goal of maximizing the overall

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benefits to be derived from the development and utilization of urban underground space [2].

Compared with above-ground space, underground space is characterized by a long development cycle, technical difficulty in construction, high construction costs, and a long-term socioeconomic impact [3]. Therefore, the development of underground spaces requires feasibility studies from multiple perspectives, prudent decision-making, and sound policies and regulations, planning and design, technology and equipment, and construction and operation systems. To clarify the relationship between responsibilities, rights, and benefits in the development and utilization of underground space, it is important to explore the problems in the comprehensive management system of underground space development in China in both the present and the future and propose a scheme for the comprehensive management of underground space development.

2 Current status of and existing problems with the comprehensive management of underground space development in China

2.1 Current status of the comprehensive management of underground space development in China

2.1.1 China as a worldwide leader in underground space development

Compared with Europe, the United States, and other developed countries and regions, China is a latecomer in the development and utilization of urban underground space. With the growing demand for underground space development in recent years, China now ranks among the top countries in the world in terms of the scale and total volume of development as well as the level of development of underground complexes and underground transportation hubs. From 2016 to 2019, a total of 1.07×10^9 m^2 of underground construction space, or 1.26 m^2 per capita, was added to Chinese cities [4]. Urban rail transport is a major demand in the context of the development and utilization of urban underground spaces, and China is leading the world in all aspects of this field [5]. As of December 31, 2020, the total mileage of China's urban rail lines reached 7715.31 km, with 5189 operating stations, while the total mileage of the country's subway lines exceeded 6300 km [6]. Currently, China's urban rail transport system is a strong driving force for the development of urban rail transport worldwide.

2.1.2 China's world-leading underground space construction technologies

In recent years, China has achieved leapfrog development in mechanized construction technology and equipment for urban underground space development (such as shield and shaft sinking) and has joined the ranks of the world's technological leaders. We have made notable advances in terms of the shield tunneling method as well as safety control technology for proximity construction and have taken enormous steps forward in the development of jacking technology, non-excavation technology, and underwater immersed pipe technology. China has also led the global development of ground displacement and deformation control technology, established itself as a world leader in terms of extra-long mountain ridge tunnel construction technology, large-section jacking technology, and underwater immersed pipe tunnel technology, and reached the world's highest level of advancement in terms of ventilation technology for gas tunnel construction, soft-rock large-deformation control technology, tunnel sinking machine construction technology, and full-section shield construction technology [7]. The development and application of a large number of new technologies have led to notable improvements in the geological adaptability and efficiency of underground engineering construction in China.

2.1.3 The emergence of a legal and regulatory system for underground space development

China has laid the groundwork for a legal and regulatory system for underground space centered on laws and administrative regulations and supplemented by departmental rules and normative documents, including the following. (1) The *Civil Code of the People's Republic of China*, the *Land Management Law of the People's Republic of China*, and other fundamental laws have made it clear that urban land is state-owned and that the land ownership and use rights are separate, which lays the jurisprudential foundation for the confirmation of space rights. (2) Although underground space is not been mentioned in the main body of China's administrative regulations, the *Notice of the General Office of the State Council on the Issuance of the Outline for the Construction of a Strong Sports Country*, the *Opinions on Promoting the Innovation Upgrade of National-level Economic and Technological Development Zones and Creating a New Highland of Reform and Opening-up*, and other normative documents have all referenced it. (3) The *Regulations on the Management of Urban Underground Space Development and Utilization* and other rules have set the principles for managing the development and utilization of urban underground space, clarified the pre-existing procedures of underground space construction, and regulated the management of underground space projects. (4) To regulate

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underground space management, various types of local normative documents have been introduced in China, and many cities have formulated regulations on the development and utilization of urban underground space. For example, cities such as Shanghai, Tianjin, and Changchun have introduced local regulations; 16 cities, including Shenzhen, Nanjing, and Guangzhou, have promulgated local government rules; and 28 cities, such as Chengdu, Luoyang, and Changsha, have issued local normative documents. These local rules have contributed to the management of urban underground space.

2.1.4 Continued improvement of underground space development planning

To meet the growing demand for underground space development in China, we have established a relatively extensive planning system based on the general traditional planning framework, which consists of master, detailed, and special plans. About 50% of Chinese cities have developed both master and detailed plans for their underground space [8]; these can be generally summarized as follows: (1) Cities like Jinhua and Tianjin have formulated a master plan for underground space with no clear relationship to the city’s overall development plan; however, the majority of cities, such as Guangzhou and Hangzhou, have developed plans for underground space as part of the city’s overall development plan. (2) Detailed plans for underground space development can be divided into detailed site construction plans (site plans), detailed regulatory plans (regulatory plans), or sections concerning underground space planning within the site/regulatory plan. Some cities only require the preparation of regulatory plans for the development and utilization of underground space. Other cities, such as Wuxi, Ningde, and Nanchang, do not explicitly require the preparation of underground space plans; however, when the right to use underground space is granted, additional planning conditions are imposed to constrain and regulate the development of underground space. (3) Additionally, some cities require the preparation of underground space plans for construction planning, urban design, and project programs. Although different types of plans vary in scope, depth, and hierarchy, and their role in guiding and regulating the actual development activities of underground space and the results of their implementation are also at different levels, all of them have played an important role in solving practical problems. The experiences and practices of various localities have provided the basis for the formulation of authoritative and normative laws and regulations nationwide [8].

2.1.5 Continuous improvement of the underground space operation management model

With the diversification of underground space development, the model of underground space operation management is constantly being innovated and improved. Specifically, (1) the investment and financing models are being enriched. Based on different investment and financing actors, two types of investment and financing models for the development and utilization of urban underground space, namely government-backed and market-based, have gradually taken shape and become polarized. The market-based investment and financing models include the build–operate–transfer (BOT) model, the transfer–operate–transfer (TOT) model, the transfer–build–transfer (TBT) model (BOT+TOT), and private financing models. (2) The construction management model has been improved. Management models based on design–bid–build, design–construction, project management contracting, design–procurement–build, construction–management, and other key elements have been developed. (3) The operation model is maturing, and three models, namely full government stewardship (the state-owned model), entrusted operation (the public–private partnership model), and market-based operation, have become dominant. (4) Demand for government regulation models is increasing. As a public good, underground space is defined by the typical features of externalities and natural monopolies and is prone to market failures, which has raised the requirements for government supervision and management, while also driving continuous innovation of the government regulation model. Overall, the underground space operation management system has been strengthened, the operation management model is benefiting from constant innovation, and the performance of operation management is improving at an accelerated pace, which has contributed to the more standardized and efficient development and utilization of underground space.

2.1.6 The increasingly visible comprehensive social impact of the development and utilization of underground space

Under the dual constraints of accelerated urbanization and growing ecological requirements, the status and comprehensive effects of the development and utilization of underground space are becoming increasingly visible [9]. Underground space development and utilization can help solve an array of critical problems that cities face by potentially mitigating traffic congestion and parking difficulties, alleviating air pollution, improving the urban environment, strengthening infrastructure protection, improving cities’ livability, and guaranteeing their normal functioning. Furthermore, underground space expands urban space and relieves land pressure. For example, the construction of underground and semi-underground substations, sewage treatment plants, and other infrastructure can save a large amount of urban land for landscaping. Moreover, underground space improves cities' disaster preparedness and resilience, strengthens the underground material reserve system and the underground disaster prevention space system, and provides safeguards for the safe development of cities. Underground space also helps drive economic growth, increase employment, and empower industries. In other words, the development and utilization of underground space provide a strong boost to economic growth, industrial development, and employment opportunities, serving as a key driving force for the Chinese economy.

2.2 The main problems with the comprehensive management of underground space in China

2.2.1 Unclear ownership and the lack of effective legal protection

At present, the main legal problems pertaining to urban underground space include the following: The legal system does not clearly define the operation rights and ownership of underground space, the legal subjects are unclear, and the management standards are incoherent [9]. Specifically, at the state-law level, a complete legal system is yet to be established. Furthermore, there is no upper law for urban underground space, and the poor coordination and harmonization among various special laws have affected their operability; there is still no legal basis for the confirmation, transfer, acquisition, registration, and protection of underground space rights. In terms of motivation for legislation, macro policies are the most impactful. Formative conditions outstrip content conditions in legislative practices, with lower-level legal documents and fewer normative and policy implementation rules; moreover, the formulation of national standards and norms lags behind the development of urban underground spaces [10]. The incomplete legal framework and insufficient basis for management are inconducive to the rational development and utilization of underground space resources.

2.2.2 Insufficient top-level design and lack of integrated planning

Regarding the implementation of development plans, the role of underground space planning in urban development has not been fully established. Specifically, (1) the research on planning itself has not been well organized and is not sufficiently in-depth, as evidenced by the inadequate research on the planning of integrated underground space development and the slow progress of the coordinated planning of over-ground and underground spaces as well as that of the networked development and utilization of underground space. (2) A lack of coordination in planning, a lack of integrated resource distribution, and the absence of an orderly connection between planning, construction, and management in the development and utilization of underground space have, in combination, resulted in the repeated excavation of some underground spaces, wasting resources and negatively affecting subsequent development and utilization. Furthermore, (3) poor feasibility and operability arise as consequences of the absence of clear methods for determining the scope of underground space property rights and the registration of such rights. This has made it difficult to transfer and assign land plots, ultimately affecting the project's operability. Moreover, due to the unclear management responsibilities of the relevant planning authority, the approval of underground space projects lacks efficiency, which hinders the orderly development of underground space [11]. (4) Planning lacks the support of forward-looking research. Most cities' underground space plans are aimed at supplementing and reinforcing the functions of ground space, with no consideration to the development and utilization of underground space in the context of sustainable urban development. There is also a lack of systematic and long-term plans for the development of geothermal resources, underground mineral resources, and historical and cultural resources, which has made it difficult to effectively control and coordinate urban space from the perspective of sustainable development [12].

2.2.3 The absence of a full picture of the available underground resources and a lack of innovation in the management and operation model

At present, most cities in China do not conduct surveys on the resources of underground space systems. Though some cities have carried out such surveys, they have only collected information about recent development and construction, while knowledge about development and utilization in the earlier period remains insufficient; in sum, the scope of the existing surveys is not full coverage, and the accuracy of the survey results is not up to standard. Moreover, there is a lack of effective communication and sufficient data sharing among different departments, and the scope and criteria used in statistics are inconsistent. All of these factors have resulted in the slow progress of underground space surveying in certain localities, making it difficult to obtain a full picture of the available resources [13]. Additionally, with the rapid progress in the development and utilization of urban underground space, the operational management of underground space faces the following problems: (1) There exists a lack of coordination among the competent departments overseeing

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the development and utilization of underground space; that is, they do not share information with each other, and each uses a different set of data. A unified regulatory and coordinating agency and mechanism are yet to be established. (2) The divided responsibilities of various regulatory departments have caused both overlapping regulation and a regulatory dearth. Due to conflicts of interest among various regulatory departments, it is often difficult to achieve regulatory synergy. (3) The operation management system lacks innovation. The unitary model of investment, which is mostly undertaken by the government, cannot attract sustained capital input and lacks an effective cost-constraint mechanism. Therefore, it cannot fully stimulate private investors' participation in financing and operation. (4) Inadequate safety supervision mechanisms increase the difficulty of executing coordinated emergency management. Except for civil air defense projects managed by civil air defense offices (civil air defense bureaus), no other underground space has been included in the overall emergency management system of cities, and a safety supervision mechanism is yet to be established, all of which make it difficult to coordinate an efficient disaster response. The above problems have added to the cost of operation and supervision, reduced regulatory efficiency, and increased the possibility of conflict over underground space rights, ultimately restricting the effective development and utilization of underground space resources [14].

2.2.4 The inadequacy of the special geological survey of underground space and the consequential difficulty of avoiding geological disasters

The development and construction of urban underground spaces are vulnerable to the impact of geological environmental factors, such as geological structure, underground water bodies, and geotechnical characteristics. Detailed geological data are needed as basic support in both the preliminary planning and design stages, as well as in the subsequent development, construction, operation, and management stages. At present, geological surveys are still inadequate in most Chinese cities, and the existing information about the geological situation remains insufficient, which has affected the development of underground spaces. For example, there are active fractures in Beijing, Xi'an, and Lanzhou; there is karst collapse in Guiyang, Wuhan, and Kunming; ground subsidence exists in Shanghai, Suzhou, Tianjin, and Ningbo; and ground fissures are present in Xi'an, Taiyuan, and other cities, all of which have caused a series of problems in underground space development.

2.2.5 The inability of existing construction technology and equipment to meet the complex development needs

Although China has made significant progress in terms of its underground engineering construction technology and equipment, the country is still unable to meet the development needs of underground space construction under super-large, super-long, super-deep, super-fast, plateau, and alpine conditions. (1) Regarding construction technology, China is still lagging behind in terms of research on underground space surveying and design technology, construction technology, and intelligent construction technology for use under difficult conditions, such as complex strata and crossing existing buildings. Basic research on new materials, new technologies, and underground engineering construction techniques also needs to be strengthened. Additionally, China lacks internationally recognized technical standards and a theoretical system for underground engineering construction. (2) Regarding technology and equipment, traditional equipment offers limited applicability and stability, and breakthroughs regarding key technologies to meet diversified needs are still pending. The manufacture of key components is still mostly controlled by foreign countries and faces the problems of a low localization rate, weak international competitiveness, and incomplete industrial chains. The industry's development is hindered by the lack of global planning, a low innovation conversion rate into technical outcomes, and the need to improve the mechanism for converting research and development (R&D) into desirable outcomes. Innovative breakthroughs in construction technology and equipment are vital for improving digging and excavation capabilities under different geological conditions, as well as circumstances of high pressure, high ground stress, high/low temperature, extreme hardness/softness, and other extreme and complex working conditions.

2.2.6 The consequences of unharmonized data standards and insufficient open sharing of information resources

The lack of uniform data standards to govern underground space information and the inadequacy of the open sharing of information resources have undermined the efficiency of underground space development and utilization and hindered collaborative innovation, resulting in duplicate information systems and resource wastage [14]. Owing to the lack of a comprehensive information management department and a unified standards system, the development and utilization of underground space face the problems of insufficient knowledge about basic conditions, unclear subjects and responsibilities, an inconsistent statistical scope and standards, and the fragmentation of data resources for the gathering of underground space information [14], all of which reduce the efficiency of data use, making it difficult to construct platforms for data collection, processing, analysis, and application. Underground space information is characterized by large volumes, diverse forms, mixed formats, extensive distribution, and insufficient information resources. Consequently, some data resources are only for the functional purpose of professional management, and the relevant regulatory departments are responsible for such resources' collection, storage, and use. Given that information projects are scattered and isolated, information resources are inadequate both in type and content, and information is not comprehensive. Relevant departments and organizations have exclusive copyrights to information data, and a no-sharing and no-integration phenomenon exists. Information technology systems with incomplete features have also restricted the improvement of informatization, standardization, and precision in urban underground space management.

2.2.7 Insufficient application of multi-dimensional intelligent technologies and the need to upgrade intelligent governance

The demand for intelligent technologies in the development and utilization of underground space is increasing, but the application of intelligent technologies to underground space planning and design, construction, operation, and maintenance management needs to be improved. Specifically, (1) the application of intelligent technologies to underground space development needs to be strengthened, and the innovative application of the Internet of Things (IoT), cloud computing, the building information model (BIM), AI, big data, blockchain, and other new technologies in particular needs to be deepened and expanded. Technologies or products such as multi-sensor information fusion technology, high-precision and reliable sensing technology, new intelligent sensor technology, and adaptive and demolition robots need to be further promoted, and lifecycle management and intelligent application of the "transparent crust" enabled by new technologies need to be improved as well. (2) At present, there is no integrated underground space intelligent management platform, and the development of intelligent information platforms for underground spaces is still in its infancy. An integrated management platform combining the functions of underground space database management, information update, data query and statistics, spatial analysis, emergency decision-making, and data mining is yet to be established, which makes it difficult to activate the functions of holographic perception, intelligent decision-making, and the efficient control of underground space. (3) The performance of intelligent operation management also needs to be improved, and the advantages of information perception technology (full granularity, full space–time, full object characteristics perception), information transmission technology, analysis and processing technology, and geographic information technology have not been fully leveraged in the fields of intelligent segmentation control and operation and emergency rescue.

2.2.8 The adverse social impacts have restricted the project's comprehensive benefits

Some adverse social impacts of underground engineering development have affected the derivation of the comprehensive benefits of underground construction. Specifically, (1) conflicts of interest trigger social tensions such as disputes over land concession, ownership of underground civil air defense projects, and ownership of underground parking lots in residential communities caused by ambiguous land boundaries and unclear ownership rules in the process of underground space development. (2) Accidents and disasters that cause personal and property losses, such as mud slides, floods, gas explosions, construction collapses, fires, and other emergencies, have become a major factor affecting cities' public safety, adding to the difficulties of underground space development. (3) Inadequate prevention and control results in environmental pollution, such as groundwater pollution, traffic-induced vibration, noise pollution, and soil erosion triggered by poorly organized protection measures in underground engineering construction.

3 The path to the comprehensive management of underground space in China

3.1 Development goals

China will act in accordance with the "four-pronged comprehensive strategy" and the "five-in-one" overall plan, pursue innovative, coordinated, green, open, and shared development [9], seize the opportunities provided by the "new infrastructure" and the urban renewal campaign, work to realize the goals of improving underground space management and promoting the modernization of the governance capacity and governance system in cities, consider the building of resilient cities as the theme, the protection of laws and regulations as the premise, and spatial planning as the fulcrum, and focus on implementing four priority tasks. It should strengthen the innovative application of intelligent technologies throughout the lifecycle of underground space to increase the depth and breadth of underground space development and utilization; promote deeper, integrated, and intelligent underground space development; improve the development,

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utilization, operation, and management of underground space; boost cities' comprehensive bearing capacity; and create a new pattern of underground space exploration featuring high-level development, high-quality utilization, and high-efficiency management. Going forward, the development of underground space in China will be planned in three different stages: exploratory, upgraded, and all-round development.

3.1.1 The exploratory development period (2021–2025)

By 2025, a comprehensive development and management system for underground spaces is expected to gradually take shape. A special geological survey of underground space will be the first technological breakthrough, the preliminary research of relevant legislation will steadily advance, top-level planning and coordination will progress, the operation management mechanism will be harmonized, breakthroughs will be made in the innovation of key construction technologies, core engineering equipment will become significantly more sophisticated, the technical standards and rules will be integrated and revised, and an initial comprehensive information management platform will be put in place. Additionally, new information technology will be integrated at an accelerated pace, and information concerning all aspects of comprehensive management will be seamlessly linked within a unified system. This will stimulate positive progress in terms of fostering new underground space development patterns.

3.1.2 The upgraded development period (2026–2030)

By 2030, a comprehensive underground space management system will be established. Data collection through surveys on the topic of underground space will be further improved, major breakthroughs will be made in local legislation, hierarchical planning will be effectively linked to territorial space planning, and the dynamism of diversified operations will emerge fully. China will lead the world in terms of construction technologies for use under complex conditions, breakthroughs in engineering equipment and technology will deliver visible results, technical standards and rules will see fast-paced introduction, and a fully functional comprehensive information management platform will emerge. With significantly improved intelligent applications and smooth coordination among all stakeholders, the comprehensive management of underground space will advance to a higher level.

3.1.3 The all-round development period (2031–2035)

By 2035, the comprehensive underground space management system will be finalized. A long-term mechanism for comprehensive underground space management will be formed, and the comprehensive underground space management system, as well as underground space capacity, will be fully modernized. State-level legislation will have made substantial progress, the planning of functional facilities will be of higher quality, the performance of operation and supervision will be significantly improved, China will lead the world in terms of construction technology and equipment, intelligent applications in comprehensive management will demonstrate visible strengths, the emergency response capability will be significantly enhanced, and the safety guarantee system will be more robust. The economic, social, and environmental benefits of underground space development will be further harmonized, and a comprehensive governance ecosystem featuring advanced technology, a sound legal framework, unified planning, orderly operation and maintenance, a virtuous cycle, and mutual reinforcement will be fully established and will provide strong support for the modernization of urban governance.

3.2 Development principles

The first principle involves integrated planning and sound coordination. The development and utilization of underground space should be coordinated with cities' development strategies; the scale and timing of development, as well as the development model, should be properly decided; and the construction of underground space should be steadily advanced. The development of over-ground and underground spaces should be coordinated and integrated, and the construction of over-ground and underground infrastructure should go hand in hand. Furthermore, the integrated development of regional underground space should be accelerated, and the principles of coordinated arrangement, comprehensive development, and reasonable utilization should be followed to promote the integration of various types of functional facilities and spaces in "one design scheme." The integrated development of vertical building layers and horizontally connected spaces should be encouraged to enable all-encompassing systemic development and utilization of urban underground spaces [9].

The second principle involves eco-friendly and green development. Underground space development should be based on the environmental carrying capacity and resource endowment, while prioritizing ecological protection and establishing a clear bottom line for resource development in underground space. Taking ecological safety assessment as the premise, it is necessary to ensure the reasonable and orderly use of underground space resources, pursue eco-friendly/green development, respect the laws of nature, and formulate development plans tailored to local conditions [15] based on assessment of the carrying capacity of the available resources and the environment as well as the feasibility of territorial space development. Moreover, the functions of underground space should be properly organized to ensure harmony between underground space development and management and the best use of the available resources and the environment.

The third principle encompasses multi-dimensional integration and intelligent driving. To build three-dimensional cities, the path to the coordinated development of over-ground and underground spaces should be explored, and the integration and sharing of multi-dimensional information, such as the integrated design of underground space, function coordination, spatial governance, ecological protection, safety resilience, and technological innovation, should also be advanced. Technologies such as the IoT, big data, and AI should be fully applied to empower the entire process of urban underground space planning, design, construction, operation, maintenance, and safety management and promote the integration and innovation of new technologies in the development, utilization, operation, and management of underground spaces. The power of intelligent technologies should be harnessed to promote cloud-based infrastructure, data standardization, business platforms, a platform ecology, and intelligent control to ultimately boost the efficient development of underground space and the competitiveness of comprehensive management.

The fourth principle is people-centered and focuses on prioritizing public interests. The development and utilization of urban underground space should uphold the principles of scientific, rational, and moderate utilization, whereas inappropriate development activities should be strictly controlled. The construction spaces allocated to infrastructure and public service facilities should be guaranteed on a priority basis, and the planning of municipal projects, underground transportation, civil air defense projects, and disaster prevention infrastructure should be prioritized. The need for optimal operation in cities and the development of adjacent spaces should both be considered, and people's lives and property, as well as the lawful rights and interests of underground space rights holders, should be protected [9].

The fifth principle is to achieve utilization readiness for both military and civilian purposes during both peacetime and wartime. Underground space planning should combine peacetime and wartime applications, consider the overall technical standards per civil air defense requirements, coordinate with the development of civil air defense projects and national defense facilities, ensure a smooth transition from the peacetime to wartime use of civil air defense facilities and compatibility with non-civil air defense facilities, and guarantee effective use during peacetime and contingent use during wartime, emergencies, and disasters. The management of ownership rights in the context of civil air defense projects should be revitalized through innovation, and civil air defense projects' existing assets should be better utilized to create an integrated protection system featuring the functions of war preparedness, business, and transportation. Efforts will also be made to explore the diversification of the peacetime functions of underground civil air defense and national defense projects and strengthen integrated construction, connection, and functional conversion with other underground space facilities to maximize the comprehensive benefits.

3.3 Priority tasks

3.3.1 Building China's comprehensive underground space management system

The first task is to strengthen the legal and regulatory system governing underground spaces, which entails the following: (1) It is necessary to create special legislation for underground spaces. A state-level legislation campaign will be initiated to regulate the development and utilization of underground spaces. The *Basic Law on Urban Underground Space* will be formulated to establish clear rules for land management, planning, ownership, development and construction, operation, and maintenance of urban underground space, as a component of the overarching goal of building a legal system for urban underground space in China [15]. The relevant provisions of existing laws that encompass underground space will be revised so that they can be precisely dovetailed with the special laws on underground space adopted at the state level to avoid contradictions and conflicts between lower and higher laws. (2) It would be beneficial to draw upon mature foreign experiences to improve coherence between regulations and policies. The *Land Management Law* should contain clear provisions, such as standards for underground space land transaction fees, the use rights for underground land earmarked for construction, and the registration of underground construction projects' property rights. Corresponding regulations for the planning, construction, maintenance, and safety management of urban underground spaces should be adopted to ensure that cities' underground transportation, public services, municipal pipeline networks, air defense, and disaster prevention systems can be maintained under good operating conditions after completion. Basic

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guidelines and policies, including a method for the land transfer of underground space, investment and financing methods, standards for the payment of land transaction fees, the rights and obligations applicable to development and utilization management, taxation policies, and regulations on use permits for public underground facilities, should be clearly defined, and the formulation and improvement of relevant standards and norms should be accelerated to promote the orderly development of urban underground space resources [16].

The second task is to improve underground space development planning. Within the overall framework of territorial space planning, a hierarchical system of underground space planning should be developed in all regions, with a clearly defined focus on different hierarchies. An underground space plan is a special type of plan among territorial space plans and is reflected and expressed in both the master plan and detailed urban development plans. Underground space planning must be clearly established as an important part of overall planning. Detailed planning should provide specific guidance on and means to exert control over the forms and functions of urban underground spaces, with a focus on the implementation process. Special planning can either be advanced in parallel with overall planning and detailed planning or formulated separately in key development regions. For large- and medium-sized cities, special plans for underground spaces need to be formulated in key development regions, and the competent planning departments should, based on the overall plan for territorial space and the city’s underground space development and utilization plan and zoning plan, oversee planning for the development and utilization of underground space in key regions and report to the municipal government for approval and promulgation. Additionally, the responsibilities of the planning and construction departments should be effectively defined in the form of legislation; that is, the competent government departments should be positioned as the overall planners and administrators, while the relevant functional departments assume the primary management role, and other departments participate in management as stakeholders.

The third task is to improve the underground space operation management system, which entails (1) moderate innovation in the underground space investment and financing mechanism, driving incremental investment with stock assets, attracting private investment with public investment, generating capital demand for short-term investment with long-term benefits, overcoming the conflict of diversified capital logic with system-wise credibility, and boosting the investment demands of the entire underground space; (2) exploring the new model of the market-oriented operation management of underground space; designing the operation management model according to the design logic of grading, classification, and phasing, based on the corporate operation mechanism, the market-oriented competition mechanism, and the platform-oriented integration mechanism; clarifying the relationship between responsibility, power, and benefit; improving the logical relationship between evaluation, incentive, and constraint; and promoting the reasonable division of responsibility, power, and benefit; (3) ameliorating the pricing of limited underground space resources in different zones and layers by proposing reasonable, appropriate, and operable pricing methods for underground space in different regions and at different depths; (4) strengthening the supervision of underground space operation and management; establishing a rationalized and standardized public supervision system featuring open government, orderly participation, and online supervision; utilizing information technologies and public opinion tools to improve the government’s ability to supervise underground space stakeholders; and establishing a full-fledged supervision and performance evaluation system for urban underground space [17].

The fourth task is to seek innovation in underground space technology and equipment systems, which entails (1) building a technological innovation system for underground engineering equipment, accelerating technological research aimed at producing new equipment, and prioritizing the development of special-purpose equipment in the fields of coal mining and national defense, as well as extreme equipment for the Sichuan–Tibet and Qinghai–Tibet railways, rock tunnel boring machines with shaped sections, a kilometer-grade deep-vertical-shaft full-section boring machine, a guided core drilling device with a kilometer-grade drilling rig, intelligent grouting equipment, high-voltage electric-pulse boring equipment, and tunnel lining quality inspection equipment; (2) seeking innovation in underground space development and construction technologies, exploring new theories and methods for underground space surveying and designing, improving underground space construction methods and technologies, strengthening the intelligent construction technologies used in underground engineering projects, improving the organization and management of underground engineering construction, promoting the internationalization of underground space development and construction technologies, and creating a technical standards system for underground engineering construction that is suited to China’s national conditions.

3.3.2 Improving the comprehensive management of underground space in China

First, it is necessary to pursue more technological breakthroughs through innovation regarding the comprehensive management of underground spaces. Multi-sensor information fusion, reliable and high-precision perception, new intelligent sensors, BIM, and other cutting-edge technologies can increase the intelligence of the comprehensive management of underground space and achieve the dynamic management of super-underground space covering all dimensions and the entire lifecycle. Building a comprehensive management platform based on BIM, 3S, and other technologies can promote integrated information technology applications to achieve visualized progress management, safety risk management, quality management, personnel management, material management, and cost management in underground space development. Adopting the IoT, AI, and other technologies can build a system with the functions of environment and equipment monitoring, communication, safety prevention, early warning, and forecasting, while establishing a data-driven, integrated management, service, and operation system to empower the operation and maintenance of urban underground space projects [14].

Second, it is necessary to enhance synergy across the entire industry chain. Promoting the innovation and research of core basic technologies for underground engineering can help relevant industries make breakthroughs regarding key technologies and upgrade independent and controllable technologies. Intensifying research on underdeveloped technologies can strengthen weak links in industrial development and contribute to the achievement of overtake in all areas. Furthermore, implementing the "going global" strategy can boost the competitiveness of domestic technology and equipment in the international market. Additionally, pushing for the optimization of industrial layouts can foster a complete industrial chain and enhance the synergy of new innovation chains, industrial chains, and ecological chains of underground engineering equipment. Further beneficial actions include molding industry leaders and cultivating world-class enterprises in the field of underground engineering equipment; bolstering the strength of key industries and developing industrial clusters of core key components such as main bearings and reducers; cultivating a complete industrial chain and developing high-end industrial clusters of matching products, including new materials, sensors, and hydraulic and electrical components, and strengthening the synergy of the entire industrial chain toward building an innovative underground engineering ecosystem that will support capacity building for comprehensive development and management.

Third, public participation in the comprehensive management of underground spaces is increasing, prompting the promotion of the transition from government-dominated urban governance to the participation of multiple public stakeholders, the prioritization of institutional building, and the strengthening of the mechanism for public participation in the comprehensive management of underground spaces. Additional beneficial actions include better leveraging the role of the government in urban governance; improving the mechanisms for coordinating, expressing, and protecting interests; and encouraging the public to express their needs, exercise their rights, and resolve disputes in accordance with the law in order to encourage healthy interaction between government governance, social adjustment, and resident autonomy. Moreover, while strengthening institutional building, a platform for public participation will be established to promote orderly, standardized, and effective public participation and leverage the role of resident self-governance in resolving social conflicts. Furthermore, the concept of civil society will be championed to build consensus on public participation, and greater emphasis will be placed on formulating implementation plans, constructing a public participation system, improving long-term governance mechanisms, and expanding the mandate and depth of public participation in comprehensive underground space management.

3.3.3 Accelerating the application of intelligent technologies to the comprehensive management of underground space

First, it is necessary to increase the transparency of underground space information. Adopting comprehensive exploration and three-dimensional (3D) modeling technology can accelerate the construction of transparent cities. Furthermore, aerial remote sensing, physical exploration, drilling, geological surveys, and other means of exploring geological conditions, stratigraphic structures, and existing geological problems across the country can be harnessed to evaluate the geological suitability and resource potential of the development and utilization of underground space. Additional beneficial actions include geological environment monitoring of underground spaces; the establishment of a nationwide 3D geological structure model of urban underground space as well as an urban geological environment information system and an information support platform for government decision-making regarding underground space development and utilization [18]; exploring a mechanism for data management and sharing and developing unified information standards to realize the informatization, integration, and visualization of ground and underground spaces;

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combining cities' reality and virtual space; strengthening the efficient, precise, and dynamic management of urban planning, construction, management, operation and maintenance, and emergency response; and aiming for higher standards in comprehensive urban management.

Second, it is necessary to promote the application of intelligent technologies to intelligent design, manufacturing, digging, and operation and maintenance throughout the lifecycle of underground engineering equipment. At the initial design stage, the use of a 3D collaborative design can promote the standardization, modularization, and generalization of underground engineering equipment. At the manufacturing stage, an enterprise resource planning (ERP) system, manufacturing execution system (MES), and product lifecycle management system (PLM) can accelerate the transition toward industrial networks, system integration, lean production lines, and virtual simulation in the manufacturing of underground engineering equipment. At the digging stage, the integration of data collection and storage and the use of cloud computing platforms, intelligent decision-making technology, and intelligent digging technology can facilitate online, real-time monitoring of the status of digging. At the operation and maintenance stage, big data and cloud computing technologies can enable remote, intelligent operation and maintenance services for health assessment and fault diagnosis on the cloud platform. The intelligent, digitized, and information-based daily management and safety management of underground spaces will be promoted with intelligent, digital, and information equipment and facilities.

Third, the digitization of underground space control is crucial. This entails (1) implementing full-area and full-factor control via 3D digital space, adopting rule engine technology to digitally translate space control and access requirements dictated in a natural language, and analyzing elemental objects and constraints and converting them into 3D space control rules that computers can identify and calculate to provide a reliable basis for furthering digital application to plan implementation and use control; (2) building on the mechanism for the transmission of multi-layered and all-encompassing digital planning to ensure the full connectivity of control content, establishing the spectrum of the content for transmission (elements, rules, and modes) in plans at different levels, and promoting the transition of plan implementation from "project coordination" to "regional coordination"; (3) promoting the digital reshaping of use control through digitized space and access control; establishing clear digitization requirements for space and access control based on planning; and connecting and combining different control subjects, elements, rules, and models; and properly balancing construction and non-construction activities to ensure the full implementation of "one blueprint" in the digital management of territorial space use control; (4) taking digital control as the driving force for the reform of government functions; exercising full-process use control, focusing on intelligent site selection, intelligent review, automatic generation of planning conditions, and refined program review; consolidating multiple examination, licensing, and inspection requirements to optimize the process; ensuring connectivity between the control content and development and construction activities; and improving the rationale of user control and the efficiency of administrative approval.

Fourth, it is necessary to build an integrated platform for underground space information. Adopting the IoT, AI, and other technologies can facilitate the establishment of a unified, integrated, government-led underground space information platform. Additional beneficial actions include constructing a comprehensive intelligent management platform with the functions of management, service, operation, and early warning, and cultivating the dynamic management capability of urban underground space covering all dimensions and the entire lifecycle; and developing a management platform with massive, multi-sourced, heterogeneous data on urban underground space, as well as a working platform for professional and technical personnel, a visualized decision-making support platform for government departments, and an information service platform that is open to the public; promoting the integrated demonstration of over-ground and underground data, building "transparent cities," and supporting the special querying, compiling of statistics, and analysis of underground space data to match the requirements for the refined management of underground space; supporting the multi-dimensional, integrated analysis of over-ground and underground spaces, gaining insights into every detail of urban space, organizing the auxiliary analysis and evaluation of the suitability of large building plans, and performing urban renovation and constructing new urban areas; supporting the monitoring of and early warning systems for water resources, the water environment, and water ecology, and resolving the problem of fragmented water management; supporting decision-making analysis for underground railway site selection, constructing underground railways in cities, and promoting special applications in underground spaces to facilitate the work of competent business departments; and promoting the dynamic management, real-time updating, and multi-dimensional display, visualized decision-making analysis, and public sharing of underground space data, and providing comprehensive and efficient information services and support for the planning, construction, operation, safety, and management of urban underground space.

3.3.4 Strengthening the safety management of the underground space emergency response

First, it is necessary to accelerate the planning and construction of safe and resilient cities. Beneficial actions include highlighting the forward-looking nature and guidance of advance planning to boost urban resilience, coordinating the top-level institutional planning of resilient cities, strengthening the protection and system resilience of underground space infrastructure, and enhancing a sustained rescue ability amidst region-wide emergencies as well as the long-term risk resistance capacity. Moreover, it is crucial to exercise the full-process risk management of underground space disasters, strengthen the disaster risk management capacity in keeping with "disaster reduction in normal times, disaster preparedness before disasters, emergency response during disasters, recovery after disasters," and enhance cities' fundamental resilience to major underground space disasters. Based on the existing disaster prevention and mitigation plans, redoubling efforts in this area can improve the system-wide simulation and forecast of a city's ability to cope with risks in multiple scenarios and diagnose problems. It is also necessary to enhance all city departments' pre-disaster management, disaster response, and post-disaster recovery capabilities in line with the development strategy and action plan of the resilient cities program and construct a systematic resilience mechanism that covers the entire disaster management process, that is, disaster risk management records, disaster monitoring and early warning, disaster simulation, planning and decision-making support, and post-disaster review and optimization.

Second, it is necessary to improve the underground space emergency response mechanism. Integrating underground space into a city's overall emergency management system and establishing a sound safety supervision and emergency response mechanism for underground space can ensure effective coordination and response amidst disaster-related emergencies. In the case of environmental and geological disasters caused by underground space emergencies or the development of underground space, the emergency response mechanism should be promptly activated to determine the nature and characteristics of accidents as well as the level of damage and the scope of the impact; emergency response teams should be immediately mobilized to handle the situation and organize evacuation, self-rescue, and mutual assistance.

Third, it is necessary to ensure effective safety supervision of underground space, which entails (1) improving underground space safety facilities, demarcating reasonable evacuation and refuge spaces and escape routes, erecting guide signs, and securing firefighting equipment, non-stagnant water channels, smoke detection equipment, sprinkler equipment, and internal firefighting channels in preparation for various types of disasters such as fires, floods, explosions, and collapses; (2) strengthening the detection, monitoring, and maintenance of underground engineering structures; establishing an early warning and monitoring mechanism for underground pipelines, subways, and other lifeline projects; strengthening risk detection in municipal pipelines, such as oil, gas, and water leakage and drainage pipeline leakage and rupture, as well as pipeline repair and maintenance; investigating the (mis)connection of rainwater and sewage pipelines; and promoting rainwater and sewage diversion; and (3) establishing a system comprising administrative institutions and a special agency in charge of the safety supervision of urban underground space and clarifying the content, system, and measures pertaining to underground space safety supervision, as well as the main safety responsibilities of various departments. Finally, strengthening information communication and sharing will reduce the likelihood of problems such as fragmented or overlapping management and the absence of management [19].

4 Policy suggestions

4.1 Establishing a unified state-level coordination mechanism for the comprehensive management of underground space, complemented by the formulation of special plans

It is recommended that the National Development and Reform Commission take the lead in establishing an inter-agency institution involving the relevant ministries at the forefront of the development and utilization of underground space in China as well as the coordination of major issues concerning underground space development and utilization, including policy documents, laws and regulations, project planning, and resources census-taking. Additionally, a national expert committee on underground space development and utilization can be established to conduct strategic and forward-looking research with the aim of preparing development strategies and policy recommendations for the future. Furthermore, top-level design and planning can be strengthened based on territorial space planning within a system containing five levels and three types of territorial space plans. A national plan for urban underground space should be introduced as soon as possible and should reflect the principles of

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equal emphasis on development and protection, the coordinated development of ground and underground spaces, vertical stratification, and horizontal connectivity.

4.2 Improving laws and regulations, standards and norms, and the regulatory evaluation system

Beneficial actions include accelerating the establishment of a legal framework for underground space, actively promoting the revision of laws related to underground space management, and incorporating the guidelines, principles, and foundational systems of underground space management into the existing legal system; revising or promulgating local laws and regulations to provide practical cases for the revision or formulation of upper laws; formulating technical standards with a focus on engineering construction under complex geological conditions; establishing complex environmental protection; developing deep underground space; ensuring the safe operation, maintenance, and renovation of underground facilities; and establishing a system of unified standards integrating underground space planning, design, construction, disaster prevention and mitigation, and environmental protection; improving higher regulatory departments' evaluation and reward and punishment mechanisms regarding their supervision of lower regulatory departments, as well as the mechanism for the regulation of underground space operators by the directly responsible regulatory departments and the mechanisms of public and media supervision; and accelerating the creation of a sound performance evaluation system for urban underground space regulation.

4.3 Accelerating research on critical and core equipment and technology and training of professionals

Beneficial actions toward this goal include maintaining the trend of underground space management in Chinese cities, which entails the development of larger, deeper underground spaces over a longer timeframe; coping with complex geological conditions, extreme environments, and other major challenges; closely adhering to the requirements of information-based, collaborative, green, and multi-layered development; focusing on priority tasks; and identifying the core basic technologies and underdeveloped key technologies for the development and utilization of urban underground space and the manufacturing of engineering equipment; establishing a technology-based system for the development and utilization of urban underground space, optimizing the industrial layout of engineering equipment, and incorporating the industry into major national R&D programs and special equipment manufacturing projects; strengthening training for relevant professionals at universities, scientific research institutions, and enterprises to meet the country's urgent need for the comprehensive management, development, and utilization of underground space; and compiling a team of first-class professionals to build a stronger capacity for the development, utilization, and comprehensive management of underground space.

4.4 Conducting an urban underground space census and implementing information-based management

There exists an urgent need to conduct a comprehensive census of urban underground space, while also establishing a census coordination mechanism and formulating a census implementation plan as well as relevant technical standards. This endeavor entails the use of advanced sensing tools to conduct a nationwide survey of the characteristics of underground space; the establishment of an evaluation system to determine the geological suitability and resource potential of underground space development and utilization based on advanced geological environment monitoring and forecasting; the adoption of modern and new information technology; the building of data management and sharing mechanisms, giving full scope to the advantages of big data in analysis; the creation of an information platform to support government-led decision-making on the development and utilization of underground space; and the development of unified information standards. In conclusion, the scientific, efficient, precise, intelligent, and dynamic management of underground space utilization can boost cities' operational efficiency and the performance of comprehensive urban management.

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References

[1] Wang X, Huang X J, Zhen F, et al. Evaluation on development potential of urban underground space resource: Multi-level grey approach [J]. Journal of Tongji University(Natural Science), 2009, 37(8): 1122–1127. Chinese.
[2] Zheng H D. Study on the management system reform of urban underground space development and utilization in Guangzhou City [J]. Chinese Journal of Underground Space and Engineering, 2013, 9(1): 7–12. Chinese.
[3] Broere W. Urban underground space: Solving the problems of today's cities [J]. Tunnelling and Underground Space Technology, 2016, 55: 245–248.
[4] Center for Strategic Consulting of Chinese Academy of Engineering, Sub-society for Underground Space of Chinese Society of Rock Mechanics and Engineering, Chinese Society of Urban Planning. Blue book of urban underground space development in China 2020: Public edition [R]. Beijing: Center for Strategic Consulting of Chinese Academy of Engineering, Sub-society for Underground Space of Chinese Society of Rock Mechanics and Engineering, Chinese Society of Urban Planning, 2020. Chinese.
[5] Cheng G H, Wang R, Zhao M H, et al. Present situation and developmental trend of urban underground space development and utilization in China [J]. Earth Science Frontiers, 2019, 26(3): 39–47. Chinese.
[6] Ma Y D. Study on the influence of driving environment vibration of single and double track tunnels [D]. Beijing: Beijing University of Technology(Master’s thesis), 2021. Chinese.
[7] Guo S Y. Technical development and outlook of the tunnels and underground works in China [J]. Modern Tunneling Technology, 2018, 55(S2): 1–14. Chinese.
[8] Zhao X S, Yang T. Discussion on planning and management of urban underground space in China [C]. Qingdao: 2013 Annual National Planning Conference, 2013. Chinese.
[9] Ministry of Housing and Urban-Rural Development of the People’s Republic of China. The 13th Five-Year Planning for the development and utilization of urban underground space [EB/OL]. (2016-05-25)[2021-04-10]. http://www.mohurd.gov.cn/wjfb/201606/t20160622_227841.html. Chinese.
[10] Zhang Z F, Liu H, Chen Z L. Overview of urban underground space development in China in 2016 [J]. Urban and Rural Development, 2017 (3): 60–65. Chinese.
[11] Peng F L, Qiao Y K, Cheng G H, et al. Current situation and existing problems of and coping strategies for urban underground space planning in China [J]. Earth Science Frontiers, 2019, 26(3): 57–68. Chinese.
[12] Liu T K, Zhou P. Suggestions on strengthening and standardizing underground space planning and development [J]. Land and Resources Information, 2019 (8): 3–7. Chinese.
[13] Sun X L, Wei B X. Reflections on strengthening the management of urban underground space resources [J]. Natural Resource Economics of China, 2017, 30(4): 26–29. Chinese.
[14] You X H, He G Y, Wang Q X, et al. Current status and development trend of urban underground space in China [J]. Tunnel Construction, 2019, 39(2): 173–188. Chinese.
[15] Wu K J, Zhao Y T, Shi X D. Research on underground space planning compiling under territory spatial planning system [J]. Tunnel Construction, 2020, 40(12): 1683–1690. Chinese.
[16] Cheng W J. Study on management system of urban underground space development and utilization—Case study from Shanghai [D]. Shanghai: Shanghai Jiaotong University(Master’s thesis), 2015. Chinese.
[17] Song B J, Wang L. Study on the safety regulation of the operation of urban underground space in the process of urbanization [J]. Collected Essays on Finance and Economics, 2016 (4): 98–104. Chinese.
[18] Zhang H W. It will realize the above ground and underground integration and make the urban underground space transparent [N]. Chengdu Daily, 2018-11-05(03). Chinese.
[19] Yi R, Jia K G. Discussion on the safety of urban underground space in China [J]. Geology and Exploration, 2020, 56(5): 1072–1079. Chinese.