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A study on the current status, challenges, and development trends of underground space development and utilization

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Abstract. With the acceleration of urbanization and the increasingly severe shortage of land resources in China, the development of underground space has emerged as a key strategy to alleviate urban development conflicts. It plays a vital role in mitigating the "metropolitan maladies" and optimizing the spatial layout of national territory. However, various issues in underground space development have become increasingly prominent, including inadequate planning systems, poor functional coordination, pronounced safety risks, and fragmented management mechanisms. Moreover, China's urban underground space development remains at an early stage, with a low degree of integration between above-ground and underground spaces, and a relatively weak resilient disaster prevention system. This study analyzes key factors affecting the effectiveness of underground space development and proposes targeted strategies to enhance overall outcomes. These include improving institutional frameworks, promoting the integrated application of BIM and GIS technologies, constructing digital platforms, and facilitating green and low-carbon transitions. The research also offers theoretical insights to support the refinement of the Regulations on the Development and Utilization of Urban Underground Space. In the future, technical approaches can be further validated through integration with smart city pilot initiatives.

Keywords: functional coordination, BIM + GIS technology, resilient governance, green and low-carbon transition, full life-cycle management

1. Introduction

1.1. Research background and significance

With the accelerating pace of urbanization, the increasingly acute shortage of land resources has become a pressing global issue. The continuous growth of the world's population, coupled with the concentration of economic activities, has led to a massive influx of people into urban areas, thereby driving rapid urban expansion. However, due to constraints imposed by natural environmental conditions and the need for ecological protection, the supply of available land is insufficient to meet the ever-increasing demands of urban development. This contradiction is particularly evident in rapidly developing countries. As one of the most populous nations in the world, China faces a critical bottleneck in the form of land scarcity, which severely restricts the sustainable development of its cities. Excessive urban sprawl has resulted in traffic congestion, environmental pollution, and other urban maladies, further exacerbating the already immense pressure on land resources.

To address this contradiction, the development of underground space has gradually garnered widespread attention. The rational utilization of underground space not only provides additional spatial support for urban development but also reduces the excessive occupation of surface land resources, thereby improving the rationality of urban spatial planning. The construction of underground transportation infrastructure—such as subways and tunnels—not only greatly alleviates surface traffic congestion but also avoids further encroachment upon surface land. Moreover, underground commercial complexes and public service facilities enhance the diversity and convenience of urban functions, fostering greater economic vitality. The development of underground space promotes a three-dimensional model of urban growth, shifting from traditional horizontal expansion to vertical spatial development. This transformation is of significant importance to advancing the sustainability of urban development.

Scholars such as Peng Fangle and Qiao Yongkang [1] have emphasized that, in the context of a new stage of development, the utilization of urban underground space holds strategic importance. It plays a critical role in addressing "urban maladies," optimizing the urban ecological environment, and enhancing urban resilience. Due to its constant-temperature characteristics, underground space offers significant advantages in energy conservation, substantially reducing energy consumption for heating and cooling. At the same time, by decreasing the density of above-ground buildings, the development of underground space frees up more green and open areas on the surface, contributing to the improvement of urban ecological conditions. Furthermore, underground spaces also serve disaster prevention and mitigation functions—such as underground shelters and emergency corridors—which are vital in responding to natural disasters and unexpected events, thereby strengthening a city's resilience to disasters. These features align closely with the strategies aimed at alleviating urban diseases [2]. Thus, underground space development is not only an effective solution to the problem of land scarcity but also a core strategy for promoting the green, low-carbon, and sustainable transformation of urban development.

2. Current status of underground space development and utilization

2.1. Overview of global underground space utilization

From the perspective of underground space utilization, developed countries have accumulated a wealth of valuable experience. A study on underground space development in Qingdao [3] shows that in advanced international cities such as Tokyo and Oslo, the use of underground space has evolved from single-function applications to multifunctional and integrated development, encompassing transportation, commerce, disaster prevention, energy, and other domains. Tokyo's approach is particularly representative. As of 2023, the total length of its subway network exceeds 300 kilometers, and it operates the world's busiest metro system in terms of passenger volume [4], forming an efficient and highly accessible transportation network. Additionally, Tokyo boasts over 50 underground commercial streets, with a combined area of approximately one million square meters. These commercial spaces are seamlessly connected to metro hubs, creating a "station-city integration" model [5]. In the construction of utility tunnels, Japan has adopted multi-layered, three-dimensional designs that consolidate electricity, telecommunications, water supply, and other pipelines into unified underground corridors, significantly minimizing the disruption of surface construction on urban life. Nordic countries emphasize regional characteristics in their underground development. In Oslo, Norway, geothermal systems have been employed to optimize energy consumption. A geothermal well cluster reaching depths of up to 300 meters now supplies approximately 20% of the city's heating needs [6]. Meanwhile, in the field of disaster prevention and mitigation, Oslo has implemented intelligent monitoring technologies—such as sensor networks to monitor groundwater levels and geological activity in real time—echoing the "comprehensive-to-key region" planning transmission system proposed by Zhao Yi and colleagues [7]. These cases demonstrate that developed countries have shifted from single-function utilization to multifunctional and integrated development of underground space, embodying the principles of sustainable urban growth.

Compared with developed countries, the challenges faced by developing nations are even more pronounced. Aside from China, most developing countries often encounter issues such as funding shortages, technological gaps, and a lack of management expertise in the process of underground space development. Due to their relatively late start in infrastructure construction, these countries frequently suffer from unsystematic planning and utilization of underground space. Furthermore, limitations in accessing advanced international technologies and expertise have compounded the difficulties of development. Although China has made rapid progress in this field, it continues to face structural contradictions. Problems such as insufficiently coordinated planning and evident technological bottlenecks remain. Complicated geological conditions, unclear delineation of property rights, and inadequate financial investment further intensify the difficulty of development and the complexity of management. To improve the situation in developing countries, efforts must focus on strengthening policy guidance, fostering technological innovation, and enhancing international cooperation in order to achieve efficient, safe, and sustainable development goals.

2.2. Major application fields

Underground transportation infrastructure constitutes the core system sustaining the efficient operation of cities. Taking urban rail transit as an example, its ability to transport tens of millions of passengers daily has significantly reshaped urban mobility patterns. Underground rail systems serve as a fundamental measure to alleviate surface traffic congestion [5]. The Tokyo Metro system, with a total length of 292.2 kilometers, records a passenger density of 103,000 person-trips per kilometer per day [8], effectively relieving the pressure on surface transportation. In Norway, the Lærdal Road Tunnel set a world record with its length of 24.5 kilometers, and its integration of a particulate filtration system and positive-pressure ventilation design ensures both safe and smooth passage. Shanghai's North Bund Tunnel Project employs a double-deck tunnel structure to integrate intelligent traffic signal control with an emergency evacuation system, resulting in over a 40% increase in traffic efficiency. This system shares a common technological foundation with the "Transparent Qingdao" smart operation and maintenance platform [3].

Underground space also fulfills complex commercial and municipal functions, serving as a critical carrier for the vertical expansion of urban capabilities. The Montreal Underground City, for instance, links over 2,000 commercial establishments through a 32-kilometer pedestrian network, forming a three-dimensional business district that complements the surface-level central business district (CBD) [9]. China's first subsea comprehensive utility tunnel was constructed in the Xiang'an New

Airport area in Xiamen [10]. It integrates eight types of utility pipelines—including electricity, telecommunications, and gas—resulting in a 60% improvement in operational efficiency and providing a robust foundation for smart city infrastructure. In the field of disaster prevention engineering, underground facilities such as the Tokyo Dome Underground Plaza are equipped with seismic isolation bearings and emergency supply storage systems, capable of accommodating tens of thousands of people for several hours in emergency sheltering. These features reflect the planning concepts of a resilient city.

Underground space, owing to its unique functional advantages, has further expanded the scope of urban service capabilities. The Lefdal Mine Datacenter in Norway utilizes the constant-temperature properties of geological formations to reduce cooling energy consumption, achieving an exceptionally high annual average Power Usage Effectiveness (PUE) of 1.1 [7]. In China's Huang-Huai-Hai Plain, a network of underground grain storage facilities has been established, using nitrogen-controlled atmosphere and low-temperature storage technologies to reduce grain loss rates to below 1%. At Singapore's Changi NEWater Plant, the underground treatment unit processes 800,000 cubic meters of wastewater daily, while the above-ground space has been restored as an ecological park—achieving both land-use efficiency and ecological enhancement.

2.3. Development trends

To overcome the bottleneck of land resource scarcity, cities are adopting three-dimensional underground space development as a key strategic approach. As shallow underground spaces gradually reach saturation, the strategic importance of deep underground space has become increasingly prominent. Deep underground space (exceeding 50 meters in depth) represents a strategic urban resource, requiring the integration of three-dimensional geological modeling and tiered land lease systems to facilitate development [6]. Cities such as Tokyo, Japan, and Helsinki, Finland, have successfully established a vertical stratification system consisting of "shallow-level transportation—mid-level municipal facilities—deep-level storage." They have undertaken extensive excavation of rock formations deeper than 50 meters to support energy storage and logistics network construction. This development process relies on technological innovations including three-dimensional geological modeling and high-pressure jet grouting pile support, while integrating property rights delineation with tiered land leasing systems. This promotes a transition from traditional planar spatial layouts to three-dimensional, multifunctional spatial organization. For instance, the Shanghai Hongqiao transportation hub adopts a five-level underground development model, combining transportation interchange, commercial services, and municipal utility corridors, resulting in a substantial increase in floor area ratio (FAR).

The multifunctional integrated development model is comprehensively reshaping the organizational structure of urban space. The functional coordination between above-ground and underground spaces has evolved from mere physical connectivity to systematic integration. For example, Singapore's Marina Bay Underground City employs BIM and GIS technologies to facilitate three-dimensional coordinated design of building foundations and underground utility networks, thereby enhancing spatial efficiency. Underground complexes complement surface-level commercial districts. The Beijing Sub-Center Station transportation hub integrates subway transfers, commercial retail, and cultural exhibition functions, accommodating a daily passenger flow of up to 450,000. At the core of integrated development is the construction of resilient disaster prevention systems. Tokyo Station's underground commercial district utilizes a fiber-optic sensor network to monitor structural deformation and gas leaks in real time. Combined with an intelligent drainage system, this enables rapid disaster response.

The full life-cycle management of underground space has fully embraced green and low-carbon concepts. Ground-source heat pump systems and solar light pipe technologies have significantly reduced energy consumption. For instance, the Shanghai Oriental Sports Center features photovoltaic glass curtain walls, generating up to 2.1 million kWh of electricity annually [11]. Leveraging digital technologies has enabled innovations in operation and maintenance models. The underground utility corridors in Xiong'an New Area integrate sensor data via a digital twin platform and utilize machine learning to predict equipment failures, while simultaneously implementing ecological design strategies. Meanwhile, the London Crossrail subway project employs double-layer steel fiber-reinforced shotcrete lining, with a sprayed waterproof membrane sandwiched between the layers. This design not only enhances crack resistance and waterproof performance of the lining but also significantly reduces the use of steel reinforcement and shortens construction time [12].

3. Core challenges and contradictions

3.1. Planning and coordination aspects

Underground space development faces significant challenges in planning and coordination. The planning of underground space involves cross-departmental collaboration and requires unified standards to avoid the tendency to prioritize above-ground development over underground spaces [13]. The "vertical '1+3' and horizontal '1+N'" planning system emphasizes the importance of comprehensive resource evaluation and planning transmission across regions [14]. A central difficulty lies in the insufficient coordination among cross-regional and multi-level plans, compounded by the lack of unified standards and coordination mechanisms. This fragmentation hampers the realization of overall benefits. During phases of urban expansion, individual administrative districts typically develop plans independently without considering overall synergy. This issue is particularly prevalent in urban agglomerations and metropolitan areas. The key to resolving this problem is establishing unified planning standards and coordination mechanisms, accelerating cross-regional cooperation, and jointly formulating and implementing interregional plans to achieve resource sharing and complementary advantages.

Another prominent issue is the functional disconnection between above-ground and underground spaces. There is a lack of coordination across planning, design, construction, and management stages. A typical example is the poor connectivity between subway stations and surrounding commercial facilities. To address this, unified planning standards for above-ground and underground spaces must be established, incorporating development suitability assessment systems to enable orderly and sustainable utilization of underground space [15]. For instance, constructing integrated complexes that link underground transportation with commercial facilities can enhance actual utilization efficiency, optimize management systems, and strengthen coordination among planning, construction, operation, and management processes to achieve complementary functions.

The lagging governance mechanism is manifested in fragmented management and an underdeveloped legal framework, which urgently requires targeted improvements. Taking Nanjing as an example, underground space development faces issues such as "incomplete information systems and lack of interdepartmental coordination," necessitating strengthened comprehensive management and property rights systems. Specific recommendations include: first, clearly defining the responsibilities of each department to avoid duplication and overlap in management; second, establishing an efficient cross-departmental coordination mechanism to ensure information sharing and coordinated actions. Additionally, in light of the unique characteristics of underground space, relevant laws, regulations, and policy documents should be improved to fill existing management gaps and provide clear legal grounds for underground space development and utilization. Furthermore, regulatory oversight and law enforcement should be strengthened through regular inspections and evaluations to ensure effective implementation of management measures, thereby enhancing the overall governance effectiveness of underground space.

3.2. Technical and safety aspects

The development of deep underground space faces a series of technical bottlenecks, with geological exploration, support structure design, and environmental control being primary challenges [17,18]. Regarding geological exploration, deep strata exhibit complex and variable conditions. Traditional technologies fall short of meeting the requirements for high-precision detection. Currently, the average mining exploration depth in China is only 300–500 meters, which significantly lags behind international advanced standards [19]. Complex rock formations such as limestone and dolomite are present, accompanied by issues such as mud and rock intrusion [20], further increasing exploration difficulties. There is an urgent need to develop novel exploration technologies tailored to the complex conditions of deep geological strata to enhance both depth and accuracy of detection.

Support structure design is also confronting severe challenges. As excavation depth increases, issues related to strata stability become increasingly prominent, with frequent occurrences of strata collapse and borehole deviation [21]. High-strength and corrosion-resistant support materials have thus become critical. However, the pressure exerted by deep strata is substantial, and traditional support methods struggle to meet current demands. Technologies such as high-pressure jet grouting piles can enhance support effectiveness but involve high costs and technical requirements, necessitating further research and optimization.

Environmental control also presents a major challenge. The high-temperature and high-pressure conditions characteristic of deep geological formations pose significant challenges to equipment performance and personnel safety, and carry potential risks of environmental pollution, such as wastewater discharge and gas leakage from the strata. It is necessary to develop equipment adapted to these harsh conditions and implement effective environmental protection measures. Technologies such as ground-source heat pump systems and constant temperature and humidity control can reduce impacts on the surrounding environment; however, issues related to high costs and limited adaptability remain to be addressed.

Safety risks in deep underground space development must not be overlooked. Hazards such as fire, flooding, and geological disasters pose significant threats to engineering safety. It is essential to establish comprehensive monitoring and early warning systems—for example, deploying Internet of Things (IoT) sensors to conduct real-time monitoring of structural integrity and environmental parameters. Additionally, developing relevant risk assessment models can help mitigate potential safety hazards. Accelerating multi-departmental collaborative governance and improving the regulatory framework are crucial to ensuring the safe and sustainable development of deep underground spaces.

4. Development trends, countermeasures, and frontier practices

4.1. Three-dimensional deep development and full-chain institutional innovation

With the acceleration of urbanization and increasing land scarcity, the extension of underground space into deep layers has become an inevitable trend. Deep development can alleviate pressure on surface space and establish a scientifically precise vertical stratification pattern. Shallow layers are designated for commercial and transportation facilities, such as underground shopping centers and subway tunnels; middle layers accommodate municipal functions, including comprehensive utility corridors and drainage systems; deep layers are reserved for special uses such as energy storage and underground logistics. This system achieves a transformation from planar to three-dimensional integrated utilization, optimizing the efficiency of underground space use while reducing functional interference and ensuring the safety, stability, and reliability of facilities.

To ensure the successful implementation of deep underground space development, it is necessary to establish comprehensive life-cycle management covering planning, construction, operation, and renewal stages. During the planning phase, development objectives, functional positioning, and development sequencing should be clearly defined, with an emphasis on seamless integration of cross-regional and multi-level planning. The construction phase must strictly control engineering quality and adopt advanced technologies to guarantee structural safety. In the operation phase, maintenance and management efforts should be strengthened to ensure smooth functioning. During the renewal phase, renovations and upgrades should be advanced in accordance with urban development needs, aligning with standards for new functions. Property rights ownership and responsibilities for deep underground space development must be clarified to minimize disputes.

Technological innovation is a critical support for advancing deep underground development. Three-dimensional seismic imaging technology enables precise acquisition of geological information, thereby supporting design and construction processes. High-pressure jet grouting pile technology addresses the stability challenges of deep rock and soil masses, ensuring structural safety. Environmental control technologies such as constant temperature and humidity systems improve underground space conditions, enhancing occupant comfort. Pilot projects for deep energy storage facilities and underground logistics tunnels have been initiated to assess technological feasibility and provide momentum for sustainable urban development.

4.2. Multifunctional integrated development and resilient governance upgrade

With the acceleration of urbanization, the integration of above-ground and underground spatial functions has become a key factor in enhancing overall urban efficiency. By constructing composite urban units characterized by “spatial connectivity and functional complementarity”—such as the coordinated operation of underground complexes and surface commercial districts—resources can be optimally allocated. This integration also alleviates surface traffic congestion, improves the quality of public services, and injects vitality into the urban environment. The close integration of Tokyo’s underground shopping streets with surface transportation hubs serves as a successful example, reflecting a multi-layered and multidimensional urban functional system.

Coordinated planning is central to achieving development objectives and relies on digital collaborative design platforms such as BIM and GIS. These technologies, based on three-dimensional modeling and data sharing, eliminate information silos and functional segmentation, enabling full-process visual management and optimizing spatial layouts and functional configurations. During the planning phase, the compatibility between underground utility networks and above-ground building foundations must be comprehensively coordinated to prevent functional disjunction. In the subway construction phase, conducting geological exploration and structural analysis in advance can effectively prevent pipeline conflicts and surface subsidence. The application of digital technologies ensures that planning decisions are both scientific and rational, providing technical assurance for the harmonious coexistence of above-ground and underground spaces.

Intelligent monitoring and emergency coordination are core components of a resilient disaster prevention system. The deployment of Internet of Things (IoT) sensors enables real-time monitoring of structural safety and environmental parameters within underground spaces, facilitating the identification of potential hazards and the establishment of early warning models. Advanced monitoring systems used in underground tunnels of coastal cities accurately predict flooding during typhoon seasons and enable rapid activation of corresponding emergency response plans. By integrating fire control, drainage, communication, and other systems, a comprehensive “disaster simulation–emergency drill–rapid response” mechanism is established, substantially enhancing the efficiency of handling emergencies. The improvement of legal frameworks is a crucial support for promoting multifunctional integrated development and resilient governance. For example, the enactment of the "Regulations on the Development and Utilization Management of Urban Underground Space" has clarified rules for multi-departmental collaborative governance, ensuring regulated and orderly underground space development and providing institutional guarantees.

4.3. Green low-carbon transition and digital empowerment

Against the backdrop of global efforts to address climate change, the underground space sector is advancing toward a green, low-carbon transformation, which has become a core development direction. Due to its stability and renewability, geothermal energy is extensively utilized in regulating the thermal environment of underground spaces. Ground-source heat pump systems, employing closed-loop piping to exchange heat with underground rock and soil, provide low-energy heating and cooling solutions. These systems can reduce energy consumption by over 40% compared to traditional methods [22]. Using high-reflectivity materials, solar light pipe technology [23] channels natural light into underground commercial spaces. When combined with light-sensing adjustment systems, this can reduce conventional artificial lighting energy consumption by several multiples. From an ecological friendliness perspective, permeable concrete pavement technology allows rainwater to infiltrate underground storage modules, which, together with water purification devices, forms a closed-loop water circulation system.

This effectively mitigates the urban heat island effect and enhances flood resistance of underground spaces. Through the integrated application of these technologies, the carbon emission intensity of underground complexes is significantly lowered, facilitating their transition from energy-consuming units to carbon-neutral nodes.

Leveraging digital technologies, the full life-cycle management model of underground space is being reshaped and has demonstrated strong application potential in China's latest pilot projects, such as in Xiong'an New Area and the Guangdong-Hong Kong-Macao Greater Bay Area. For example, collaborative design platforms based on BIM and GIS can accurately simulate the structural coupling between deep underground spaces and surface buildings. Intelligent clash detection reduces construction rework rates by over 30%. Furthermore, the full life-cycle management platform integrates IoT data from construction machinery, structural health monitoring information, and pedestrian heat maps. Using digital twin technology, it achieves dynamic operation and maintenance optimization. In specific applications, AI algorithms analyze real-time data from parking lot gates and surrounding traffic flows to intelligently adjust parking space allocation strategies, thereby enhancing turnover efficiency and user convenience. In Xiong'an New Area's smart city construction, this technology has been widely applied in managing underground utility corridors, significantly improving resource utilization efficiency. In the safety domain, distributed fiber optic sensing systems combined with machine learning models can precisely monitor micro-strains in tunnel structures and predict the probability of support structure failure [24,25], reducing emergency warning response times to under 15 minutes. This technology awaits further validation in the cross-sea tunnel projects of the Guangdong-Hong Kong-Macao Greater Bay Area.

5. Conclusion

5.1. Strategic significance of underground space development for urban growth

Underground space, as a core carrier of three-dimensional urban development, has seen its strategic value evolve from a single spatial expansion dimension to a coordinated three-dimensional system encompassing spatial, economic, and ecological aspects. In the process of global urbanization, underground development, through the integration of transportation, municipal, commercial, and other functions, has effectively alleviated the tension between limited land resources and growing urban functional demands. The practice of deep underground development in Tokyo, including logistics systems and energy storage, demonstrates that establishing a vertical stratification system can increase space utilization efficiency by nearly 40% [26]. Domestically, pioneering demonstration zones such as Qianhai in Shenzhen have leveraged BIM and GIS technologies to achieve coordinated design between above-ground and underground spaces, significantly reducing conflicts between underground utility corridors and building foundations. This fully validates the technical feasibility and practical value of three-dimensional integrated spatial planning [27]. Such practices not only optimize urban spatial structures but also create new urban economic trigger points through the functional linkage of underground transportation hubs and surface commercial complexes.

Relying on the sustainable urban development framework, the strategic significance of underground space is embodied through the establishment of a full life-cycle management system. Deep underground space development has driven innovation in low-carbon technologies such as geothermal energy utilization and modular support structures. Genchi et al. conducted a comparative study of a ground-source heat pump system and an air-source heat pump system in a high-energy-consumption area of Tokyo, examining their CO_2 emissions. The study calculated that the annual CO_2 emissions of the ground-source heat pump system amounted to 33,935 tons, whereas the air-source heat pump system emitted 73,454 tons annually—indicating a 54% reduction with the former [28]. The North Bund underground complex in Shanghai employs a digital platform integrating BIM and IoT data to achieve real-time environmental parameter control, reducing risk warning response times to 15 minutes. Institutional progress is equally critical. Singapore, with its rich experience in efficient and intensive land use, implements "white land" management where planning indicators are divided into prescriptive and guiding categories. Developers can adjust land-use nature according to contracts without paying land premium fees. Land reclamation is used to reserve development land, with usage adjusted according to developmental trends. Underground space development has been elevated to a national strategic level, with layered planning dividing functions into transportation, infrastructure, and integrated complexes, supported by 3D and other technologies for information integration and pre-planning. Brownfield development incorporates evaluation and supervision mechanisms to restore ecology and enable diversified development. Furthermore, exploratory use of caves for public facilities and the development of planning tools to identify potential development zones are underway to ensure sustainable urban spatial development [29].

5.2. Coordinated pathways of technological innovation and sustainable development

Research on the development and utilization of underground space must focus on the deep integration of fundamental theories and applied technologies. Comprehensive studies of geological, hydrological, and other environmental conditions are required—for instance, employing ground-penetrating radar technology for precise detection of underground structures and formulating effective groundwater protection plans to provide a scientific basis for development. Systematic assessment of the potential ecological impacts of underground space development is necessary, alongside the establishment of effective environmental protection measures. Expanding the diversified applications of underground space in transportation, commerce, culture, and education can significantly enhance urban functions and service levels. Particularly during disaster resilience phases, the functional design of underground space should emphasize resilience building to strengthen cities' overall disaster prevention and mitigation capabilities. Analysis of domestic and international cases reveals that using underground spaces as emergency shelters and seismic-resistant facilities can alleviate pressure on surface areas and substantially reduce disaster-induced losses.

Technological innovation has become the core driving force behind the sustainable development of underground space. Future research and development should prioritize breakthroughs in construction technologies, operational management, and intelligent systems. Advances in deep support technologies can overcome development obstacles posed by complex geological conditions. The application of Internet of Things (IoT) and big data technologies enables real-time monitoring and intelligent management of underground spaces. For instance, the deployment of sensor networks in Shanghai's North Bund underground space collects environmental data in real time. Combined with big data analytics, this facilitates the prediction of potential risks, thereby significantly enhancing management efficiency and safety. The interdisciplinary integration of geotechnical engineering and artificial intelligence is emerging as a key technological trend. By combining knowledge from civil engineering, environmental science, information technology, and other fields, an integrated innovation framework is being constructed. It is essential to improve the supporting policy and regulatory system by further refining frameworks related to property rights, usage permissions, and safety management to standardize market behavior. Encouraging private capital participation and establishing full life-cycle management protocols to close the planning–construction–operation loop can greatly improve utilization efficiency and safety performance. Leveraging the synergy between technological innovation and institutional safeguards will propel underground space development toward greener, low-carbon, and intelligent directions, thereby laying a solid and reliable foundation for sustainable urban development.

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