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EXPLORATION FOR UPGRADING OF URBAN UNDERGROUND SPACE PLANNING IN CHINA: UNDERGROUND PLAN

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Abstract: Multiple major resources exist below the ground: space, water, geothermal energy, geomaterials and so on. While the necessity of using multiple underground resources (MURs) has been extensively studied. However, most Chinese cities develop the underground space plan lacking examinations assessing the interaction relationship of MURs, which hinders the policy making and planning formulation of MURs synergistic utilization. It is proposed that the urban underground space plan should be upgraded to plan MURs, that is to say underground plan. The need for the transformation and upgrading of underground space plan in China is discussed, and the types and systems of underground space plan and its related plan are analyzed. Finally, the orientation and the major components of future underground plan are put forward. This research work provides a sound understanding of MURs synergistic utilization mechanism, which is supposed to be conducive to the sustainable utilization of MURs and the formulation of MURs plan.

Keywords: Urban underground space plan, Underground plan, Upgrading, Multiple underground resources

1. INTRODUCTION

Underground space, recognized as the 'Fourth Territory' beyond a nation's land, airspace, and territorial waters, represents an emerging natural resource for urban development and a crucial strategic national asset. With contemporary urban growth constrained by existing ground-level environments, pre-existing structures (buildings and infrastructures), and finite spatial resources, the utilization of urban underground space is garnering increasing attention [1-3]. However, the academic community has gradually realized that multiple resources exist below the ground: space, water, geothermal energy, and geomaterials [4-6], as shown in Table 1. Conceptually, these resources are intrinsically interconnected within a unified underground environment. Singular resource utilization often adversely impacts the exploitation potential of others, creating conflicts, such as underground constructions forming groundwater cut-off walls that obstruct natural aquifer flow paths [7], and challenges in managing spoil from underground excavations [8]. Current underground space planning frameworks predominantly emphasize functional service domains—such as urban transportation, municipal infrastructure, and commercial facilities—while insufficiently integrating the utilization of groundwater, geothermal energy, and geomaterial resources [9,10]. China's 'Dual Carbon' goals and urban renewal initiatives now mandate transformative approaches to underground development, explicitly requiring rational groundwater utilization, geothermal resource exploitation, and construction spoil recycling. Consequently, China's urban underground pace development must transition from

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high-speed growth to quality-driven advancement—shifting from the utilization of single resource toward the synergistic utilization of MURs. To achieve this aim, underground space planning should be upgraded to the MURs planning, that is, underground planning.

Table 1. *Descriptions and Value of multiple major resources that existed below the ground [11-15].*

Type	Descriptions	Value
Underground space	The underground space is naturally or artificially excavated, remains unexploited, and has the potential to be developed under existing technological conditions.	The use of underground space could alleviate traffic jams and land shortages.
Geothermal energy	Geothermal energy refers to the thermal energy contained in rock-soil mass below the ground.	Geothermal energy is a crucial renewable energy source for constructing energy systems and reducing carbon emissions.
Groundwater	Groundwater is the water reserved in rock and earth mass fractures or holes below the ground.	Important part of water, constitutes half of the world's residential water and approximately 25% of agricultural irrigation water, and used for 38% of the world's irrigated land.
Geomaterials	Geomaterials refer to the useful materials excavated from below ground such as rock, soil, etc.	Effectively using geomaterials helps improve the environment and reduce waste.

2. MOTIVATIONS FOR PLANNING MURS IN CHINA

2.1. Intensive utilization of MURs

Driven by China's rapid urbanization and technological advancements in underground resource utilization, including ground-source heat pumps (GSHP), tunneling shields, and spoil recycling, urban underground resource exploitation has undergone accelerated development, exhibiting distinct scalability. For underground spatial resources, China's annual growth rate averaged nearly 20% from 2018 to 2023, with cumulative construction reaching 3.276 billion m^2 by end-2023; newly added underground space in 2023 alone approximated 312 million m^2, accounting for 21.8% of total urban construction completions (see Figure 1 for cumulative and annual development) [16-20]. Regarding geothermal resources, China possesses abundant shallow geothermal reserves with utilization leading globally—by 2021, its geothermal heating/cooling capacity hit 1.33 billion m^2, maintaining the world's largest direct-use scale for years [21]. For groundwater, despite stringent controls reducing supply from a 2012 peak of 113.2 billion m^3 to 81.95 billion m^3 in 2023, it still constituted 13.9% of national water supply [22-24], alongside enhanced regulatory frameworks. In geomaterials, Shenzhen exemplifies scale: engineering spoil and slurry reached 81.08 million tonnes in 2023 (≈90% of construction waste, with its Construction Waste Management Plan mandating 40.7 million m^3/year silt-separation capacity and 52.83 million m^3/year eco-sintering capability [25]. This large-scale utilization establishes the foundation for planning MURs.

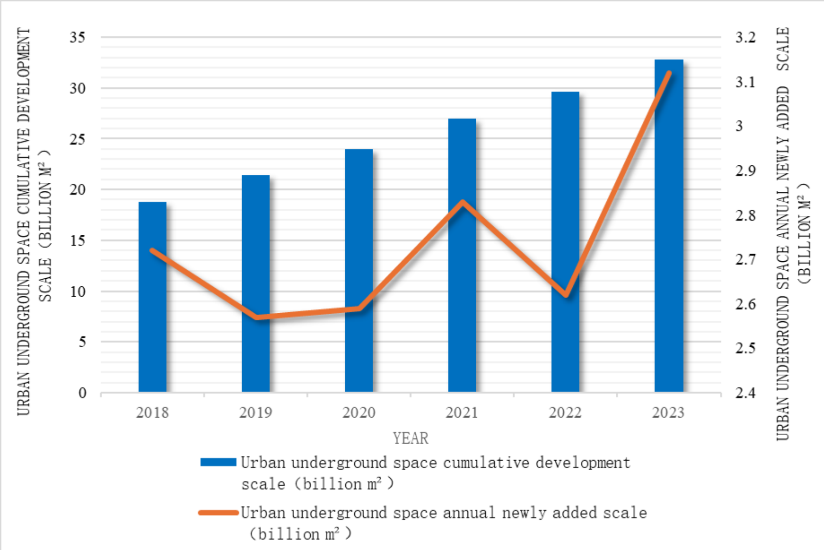

Figure 1. *Schematic diagram of cumulative development scale and annual newly added floor scale of urban underground space in China (2018-2023)*

2.2. Interactions among MURs

2.2.1. Underground space and water

Numerous studies and engineering practices have demonstrated interactions between underground space and groundwater [6,7,26-28]. The impact of underground space on groundwater primarily arises when underground engineering penetrates or traverses aquifers, forming cutoff walls that obstruct groundwater flow paths while contacting groundwater. This leads to structural corrosion, alterations in groundwater levels, and contamination [6,10,26]. Conversely, the impact of groundwater on underground space mainly stems from rising water levels due to groundwater protection or reduced groundwater extraction, thereby modifying the operational environment of underground structures originally constructed above the water table [6,28]. This compromises engineering performance and induces incidents such as sand boiling and structural failures. Specific cases and related research are detailed in Table 2.

Table 2. *The cases and studies of the interactions between underground space and groundwater.*

Type	Description of case and study	Site
Underground space to groundwater	underground space development in the Xiong'an New Area will result in the expansion and deepening of depression cones within aquifers. Groundwater levels on the upstream side of underground structures will rise, while those on the downstream side will decline, with the maximum observed water table increase reaching 7.17 m [26].	Baoding，Hebei.
Underground space to groundwater	The Chengdu University of TCM & Sichuan Provincial People's Hospital Station documented groundwater level alterations over five years post-construction, with the hydraulically upstream side exhibiting approximately 0.8 m of backwater elevation and the downstream side registering circa 0.5 m of drawdown [27].	Chengdu，Sichuan
Groundwater to underground space	The inter-tunnel section of Beijing's Jianguomen Station Metro experienced sand boiling phenomena in its foundation due to groundwater level rebound [28].	Dongcheng District，Beijing.

2.2.2. Underground space and geothermal energy

The interactions between underground space and geothermal energy primarily depends on the type of geothermal utilization facility. For ground source heat pump (GSHP) systems, their interplay manifests predominantly as spatial interference between underground structures and ground heat exchangers [15]. For groundwater source heat pump (GWHP) systems, the interaction chiefly arises from aquifer disruption caused by underground space development, which alters groundwater levels and consequently impacts GWHP operational efficiency [29]. Regarding energy geostructures, their synergy is characterized by direct integration within underground engineering frameworks, enabling geothermal harnessing without occupying additional space [30]. Specific case studies are detailed in Table 3.

Table 3. *The cases of the interactions between underground space and geothermal energy.*

Type	Description of case	Site
Underground space to GSHP	During the construction of Xuzhou Metro Line 1, the project encountered interference from pre-existing GSHP systems. This resulted in the demolition and reconstruction of the affected geothermal systems [31].	Xuzhou city，Jiangsu
Underground space to energy geostructure	In the Shanghai Foxconn Tower project, GSHP pipes were installed within the diaphragm walls forming the foundation pit support structure, creating integrated "Energy Walls." The pipes were embedded at depths of approximately 37 meters, with a pair of U-tubes installed at 1.5-meter intervals, totaling 204 loops [30].	Pudong new area. Shanghai

2.2.3. Underground space and geomaterials

The advancement of spoil valorization technology has revolutionized underground construction by enabling the recycling of excavated rock and soil materials for reuse in subgrade formation, landfill site stabilization, and ceramsite manufacturing [29], while simultaneously facilitating the repurposing of subterranean voids created during material extraction into functional underground spaces [10]. Representative cases are detailed in Table 4.

Table 4. *The cases of the interactions between underground space and geomaterials.*

Type	Description of case and study	Site
Underground space to geomaterials	The Haishu District Duantangzhong Road Project in Ningbo utilized dredged sludge and silty clay soils from engineering spoil as primary raw materials for roadbed filler, with the recycled spoil constituting approximately 92% of the final product's composition by weight and supplementary additives accounting for the remaining 8% [32]。	Ningbo，zhejiang
Geomaterials to underground space	three underground reservoirs were constructed with a total storage capacity of 7.105 million m³, achieving a daily reinjection rate of approximately 9,790 m³ of treated mine water in the Daliuta Coal Mine within Shendong Mining Area [33].	Yulin，shanxi

2.2.4. Geothermal energy, groundwater and geomaterials

Conceptually, the interactions between geothermal energy and groundwater utilization primarily stems from the fact that both resource exploitation activities require water resources. Different types of geothermal energy utilization facilities are subject to distinct impact mechanisms. For ground-source heat pump systems, groundwater extraction leads to a decline in the utilization efficiency of GSHP but does not render them inoperable, whereas for GWHP, groundwater extraction causes a drop in the water table, thereby resulting in an inability to extract groundwater for heat extraction and ultimately rendering them inoperable.

Conceptually, the existence of both geothermal energy and groundwater is intimately linked to underground rock and soil formations. Geothermal energy utilization requires heat extraction from geological media such as rocks, soil, and water, while groundwater resides within underground sediments and rock matrices. Excavation of underground rocks or soils fundamentally alters the geological substrate, causing both geothermal resources and groundwater to cease to be recoverable due to the destruction of their natural hosting environments.

In summary, both the scaled-up utilization of China's underground resources and the interactions among these resources will lead to increasingly pronounced conflicts in engineering practices while simultaneously amplifying the demand for coordinated resource management. Consequently, an integrated planning framework for the MURs becomes imperative.

3. PROJECTS FOR USING MURS

3.1. Underground space use and geothermal energy

China has now implemented multiple projects demonstrating synergistic utilization of underground space and geothermal energy. A flagship example is the Beijing Daxing International Airport, completed in 2019, which features two underground levels accommodating high-speed rail, metro, and intercity railway transfers alongside commercial and dining services. For geothermal exploitation, the airport hosts China's largest GSHP system, enabling it to achieve 10% renewable energy utilization—a key sustainability target. This system serves 2.57 million m² of space through two energy stations and 10,497 borehole heat exchangers (BHEs), with their layout illustrated in Figure 2. Annually, it extracts 303.2 terajoules (TJ) of shallow geothermal energy, saving 12.25 million m³ of natural gas—equivalent to 14,873 tonnes of coal—while reducing carbon emissions by over 24,900 metric tonnes [34-37].

Similarly in Beijing, the Dongliuhuan (Jingha Expressway-Luyuan North Street) Renovation Project completed in April 2025 transformed conventional shield tunnels into energy tunnels by integrating heat exchange pipes within the invert segments (Figure 3). This dual-functional infrastructure simultaneously bears surrounding rock loads and extracts geothermal energy. The 800-meter energy tunnel section meets heating/cooling demands for 1,226.3 m² of buildings in the South Administration Zone while providing winter de-icing for approximately 40 meters of the F6 ramp roadway [38,39].

In Shanghai, the Natural History Museum (New Wing) opened in 2015 occupies a 12,000 m² site with a total floor area of 45,275 m². The 18-meter-tall structure comprises three above-ground levels and two basement levels. This project employs energy geostructures through heat exchange pipes embedded in bored piles and diaphragm walls (Figure 4). The ground-source heat exchanger system delivers peak cooling and heating capacities of 1,639 kW and 1,178 kW respectively. Although the initial investment for this geothermal system exceeded that of a conventional chiller-boiler setup by ¥2.102 million, it achieves annual operational savings of ¥223,000 with a dynamic payback period of 11.98 years. The system reduces coal consumption by 117.7 tonnes of standard coal equivalent annually while cutting CO_2 emissions by 195.5 tonnes [31,40].

Figure 2. *Schematic Diagram of Geothermal Borehole Layout at Beijing Daxing International Airport* [35]

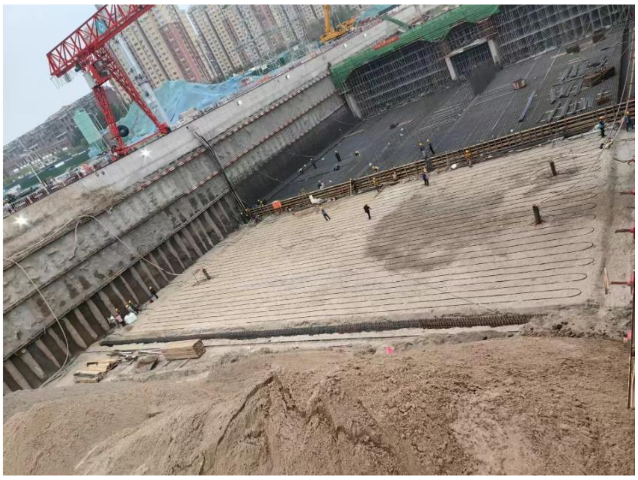

Figure 3. *Construction Site of the Snow-Melting and De-Icing Section in the Energy Tunnel* [39]

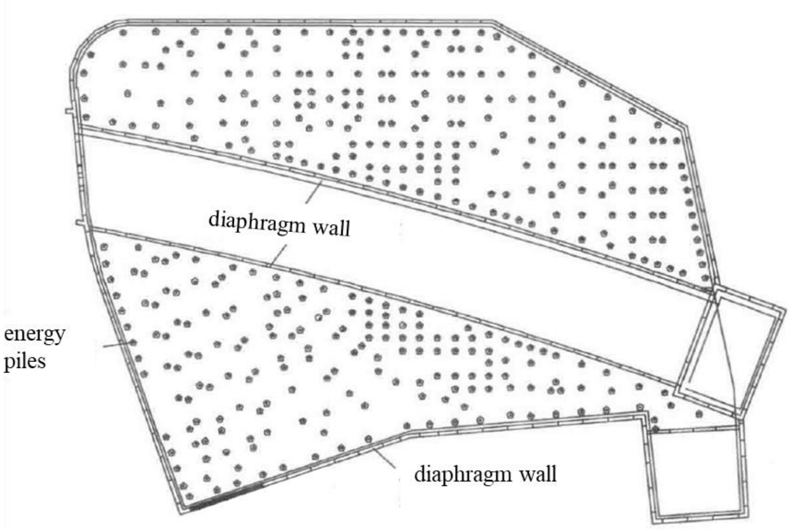

Figure 4. *Schematic Diagram of Geothermal Pipe Embedding in Cast-in-Situ Piles at Shanghai Natural History Museum* [31]

3.2. Underground space use and geomaterials

Nanjing's Southern New District, situated south of the old city beyond Zhonghuamen Gate, spans the tri-junction of Qinhuai, Jiangning, and Yuhuatai districts adjacent to Nanjing South Railway Station. This Tier-1 priority development zone—one of Nanjing's four core urban hubs—covers a planned area of 19.8 km² with a 9.94 km² central nucleus. Its underground space development totals approximately 4.8 million m², with subterranean construction accounting for ~35% of above-ground floor area [41,42]. The district pioneer's construction waste resource recovery in municipal projects, targeting 2.2 million m³ of spoil recycling. This initiative reduces diesel consumption by source, cutting CO_2 emissions by approximately 19,000 tonnes [43]. Figure 5 shows China's first large-scale stationary spoil recycling plant operational in the Southern New District.

On Shenzhen Metro Line 13, the 2.1-km tunnel segment between Yingrenshi and Luozu stations yielded approximately 206,000 m³ of excavated material, comprising 21,000 m³ of hard rock and 185,000 m³ of slurry-type soft soil. To facilitate differentiated treatment and recycling, the Line 13 Spoil Processing Center was established with a peak daily throughput of 4,000 m³. Operating at a continuous processing rate of 200 m³/h for over 20 hours daily, the center had reclaimed 27,300 m³ of reusable sand and aggregate resources by 2022 [44]. Figure 6 details its slurry separation phase within the treatment workflow.

In Kansas City, Missouri, limestone mining since the late 19th century left extensive abandoned mine workings. By the mid-20th century, mining operators transitioned from solely extracting limestone to strategically converting mined-out voids into available space resource during active excavation [29].

Figure 5. *China's First Large-Scale Stationary Construction Waste Resource Utilization Plant (Self-photographed)*

Figure 6. *Slurry Separation during Construction Waste Processing for Shenzhen Metro Line 13* [45]

3.3. Underground space use and water

Xiong'an New Area, strategically positioned within the Beijing-Tianjin-Baoding regional triangle, encompasses a planned 1,770 km² as a national-level development zone where the Hebei Xiong'an New Area Planning Outline (hereafter 'Outline') mandate comprehensive utilization of underground space and groundwater [46]. The Outline specifically requires orderly underground space utilization, prioritized infrastructure deployment in subsurface areas, and establishment of integrated coordination mechanisms. Concurrently, Xiong'an New Area Master Plan (2018-2035) construction of a groundwater monitoring network featuring 41 well clusters (109 individual wells) across the entire 1,770 km² zone, enforcing strict extraction controls to monitor and prevent land subsidence, with primary focus on shallow aquifers ≤50m depth [47].

As the pioneering development sector, the 38-km² Start-up Area—under the Hebei Xiong'an New Area Start-up Zone Regulatory Detailed Plan—limits above-ground construction to 28 million m² while capping underground space utilization below 10 million m². This zone designates groundwater as the emergency backup supply [48].

4. ANALYSIS OF CHINA’S UNDERGROUND SPACE PLANS AND ITS RELATED PLANS GROWTH TREND AND CHARACTERISTICS OF CARBON EMISSIONS

4.1. Prevailing typology and characteristics of underground space plans

Underground space plan serves as a specialized sub-system within China's territorial spatial plan framework, providing critical regulatory foundations for the utilization of urban underground space resources. Current multi-tiered underground space plans comprise: (1) underground space development plans, (2) underground components within territorial spatial master plans, (3) specialized underground utilization plans, and (4) detailed underground plans [49,50].

(1) Underground Space Development Plan

These represent the strategic blueprint guiding scientific utilization, orderly construction, and efficient management of urban underground resources over defined periods. Functioning as overarching policy documents, they establish development objectives, guiding principles, implementation strategies, key tasks, and safeguard measures - forming the fundamental basis for subsequent plan and governance.

(2) Underground Space Components in Territorial Spatial Master Plans

Derived from development plans, these components define underground plan frameworks and content requirements within comprehensive territorial plans. They provide directives for specialized underground space utilization plans and detailed underground space plans, articulating development priorities, plan philosophies, formulation depths, and compilation strategies. Crucially, they establish interfaces between underground space plan subsystems and broader territorial plan systems.

(3) Specialized Underground Space Utilization Plans

Operating under master plan guidance, these core instruments coordinate underground space development across entire urban areas. They facilitate vertical integration of plan indicators from master to detailed plans, identify regulatory priorities, and address control requirements. Key elements include spatial configurations, development phasing, objectives/strategies, 3D control mechanisms, facility classification guidance, disaster resilience measures, and implementation safeguards.

(4) Detailed Underground Space Plans

As direct implementation tools, these plans operationalize mandatory requirements from development and master plans while interfacing with specialized plans. They provide statutory bases for underground space allocation and management, offering integrated aboveground-underground development guidelines for design and construction. Content encompasses functional specifications, interconnectivity requirements, quantitative development controls, environmental/cultural provisions, facility sitting, and integrated spatial design.

Multi-tiered underground space plan necessitates coordinated utilization of diverse underground space resources according to each tier's positioning, functions, and content. This chapter analyzes existing urban underground space plans to demonstrate their multi-level responses to synergistic resource utilization, as systematized in Table 5.

Table 5. *Responsiveness of multi-tiered underground space plans to the synergy utilization of MURs*

Multi-tiered underground space plans	Underground space	Groundwater	Geomaterials	Geothermal energy	Synergy utilization
Underground space Development Plans	√	√	√	−	√
Underground Space Components in Territorial Spatial Master Plans	√	−	√	√	√
Specialized Underground Space Utilization Plans	√	−	−	−	−
Detailed Underground Space Plans	√	−	−	−	−

√ refers to involve; − refers to not involve.

4.2. Interfacing specialized plans with underground space plans

Underground space plans exhibit comprehensive nature, involving multiple specialized plans for underground development. Relevant plans such as civil defense, rail transit, municipal utilities, public services, disaster prevention, and sponge city initiatives all entail underground demands. This paper systematically reviews 16 types of urban specialized plans with underground requirements. By analyzing conflicts in underground space utilization across these plans, it proposes synergistic relationships with MURs. Conflicts between other specialized plans and underground space utilization can be categorized into [51]: ① Conflicts with underground space constraints; ②

Conflicts between specialized plans themselves; ③Conflicts arising when feedback from underground space plan outcomes is integrated into other specialized plans. Specific details are presented in Table 6.

Table 6. *Conflicts in underground space utilization among specialized plans and their synergistic relationships with MURs*

Specialized Plan	Existing Conflicts	Involved Major Underground Resources				
		Underground space	Groundwater	Geomaterials	Geothermal energy	Synergy utilization
Urban Renewal Specialized Plan	①	●	○	○	○	○
Sponge City Specialized Plan	①	●	○	—	—	○
Rail Transit Specialized Plan	②	●	●	○	—	●
Integrated Transportation Specialized Plan	②	●	—	—	—	—
Parking Facilities Specialized Plan	②	●	○	○	○	○
Logistics & Warehousing Specialized Plan	③	●	—	—	○	○
Utility Tunnel Specialized Plan	③	●	○	○	○	○
Municipal Facilities Specialized Plan	③	●	●	—	●	●
Civil Defense Facilities Specialized Plan	②	●	●	●	○	●
Seismic Disaster Prevention Specialized Plan	③	●	○	○	○	○
Mineral Resources Specialized Plan	③	○	●	●	●	●
Cultural Tourism Specialized Plan	③	●	—	—	—	—

New Digital Infrastructure Plan	②	●	—	—	—	—
Smart Infrastructure Plan	②	●	—	—	—	—
Geothermal Resource Specialized Plan	③	○	●	—	●	○
Groundwater Protection & Utilization Plan	③	○	●	—	●	○

● indicates mandatory consideration of synergy, ○ indicates recommended consideration of synergy, indicates no current need for consideration.

4.3. Issues in underground space plans and interfacing plans

Existing underground space plans and interfacing plans exhibit a multi-tiered and highly comprehensive nature, encompassing development plans, territorial spatial master plans, specialized plans, and detailed plans. By analyzing the responsiveness of underground space plans to synergistic utilization of MURs, the conflicts between specialized plans and underground space utilization, and their coordinate relationships with MURs, this study identifies the following issues in China's current underground space plan framework:

(1) Inadequate plan transmission mechanisms

While China's underground space development plans and territorial spatial master plans address MURs, their specialized and detailed plans remain predominantly focused on underground space exploitation. Insufficient vertical integration exists between plans (master plans to specialized plans), reflecting incomplete transmission mechanisms.

(2) Absence of resource synergy principles

Across all plan tiers, content prioritizes underground space resource development—covering objectives, plan concepts, facility categorization, and spatial arrangement. Synergistic utilization of other underground resources (geothermal, groundwater, geomaterials) receives insufficient attention.

(3) Fragmentation of specialized plans interfacing underground space plans

Specialized plans interfacing underground space plans encompass numerous types, functionally spanning multiple levels including transportation, warehousing, civil defense, information technology, cultural tourism, and seismic safety; resource-wise involving diverse underground resources such as space itself, minerals (geothermal inclusive), and water resources; and administratively engaging multiple departments including transportation, water resources, and geology. This cross-sectoral fragmentation characteristic within both specialized underground space utilization plans and related specialized plans thereby substantially increases the complexity of achieving synergistic utilization of MURs.

4.4. Some suggestions for upgrading of urban underground space plans

Building upon the analysis of multiple underground resource utilization projects and China’s underground space plan framework, this study proposes the following recommendations for upgrading urban underground space plan in China:

(1) Positioning specialized underground space utilization plans as the core vehicle, this approach integrates the synergistic utilization of MURs. Current analysis reveals that development plans and territorial spatial master plans have initiated the incorporation of MURs. Functioning as the primary transmission driver for plan indicators from master plans to detailed plans, specialized underground space utilization plans must transition from singular space resource plan toward multi-resource plan. Thematic coverage includes spatial layout, construction phasing, objectives and strategies, horizontal and vertical control mechanisms, development guidance, facility classification, disaster resilience, and implementation safeguards. Incorporating resources such as groundwater, geothermal energy, and geomaterials into specialized plans would significantly enhance practical engineering

guidance. Consequently, given both operational demands and engineering applicability requirements, specialized underground space utilization plans constitute the fundamental platform for future upgrades.

(2) Refining underground space plan transmission mechanisms. The transmission within underground space plan is multifaceted. It manifests not only between the master plan and specialized plan, but also between development plan and the master plan, between the master plan and detailed plan, and between specialized plans and detailed plans. Establishing a robust coordination mechanism is essential to form a coherent underground space plan system.

(3) Leveraging the coordinating and guiding function of specialized underground space utilization plans. China's current underground development involves numerous specialized plans, with most underground utilization content from interfacing specialized plans with underground space plan already addressed within specialized underground space utilization plans. This framework should activate its coordinating and guiding function to proactively mitigate inter-plan conflicts in underground space utilization while establishing explicit synergistic relationships with MURs, thereby progressively integrating multi-resource synergistic utilization principles into all interfacing specialized plans.

5. CONCLUSION

This study briefly outlined motivations for planning MURs in China, and further analyzed the current deficiencies in underground space plans and its related plans for the synergistic utilization of MURs. Recommendations are proposed, including "Positioning specialized underground space utilization plans as the core vehicle," "Refining underground space plan transmission mechanisms," and "Leveraging the coordinating and guiding function of specialized underground space utilization plans." It should be noted that China's underground space plan is characterized by its strong comprehensive nature. This characteristic becomes even more pronounced in the underground plans. Compared to conventional underground space plans, underground plans required richer geological data and greater coordination of departments. This study provides only a preliminary exploration of the framework for underground plans. More in-depth research is warranted regarding its formulation, implementation, and management.

6. ACKNOWLEDGMENTS

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