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DIGITAL INTELLIGENCE EMPOWERS THE DEVELOPMENT AND UTILIZATION OF UNDERGROUND SPACE IN MEGACITIES

Take the innovative practice of the refined management and control system of the National Exhibition and Convention Center (Shanghai) and the surrounding underground space as an example

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Abstract: This study focuses on the digital development of underground spaces in mega cities. Through the research of comprehensive risk management technology and multi subject collaborative governance system for large underground spaces with multiple and diverse functions, a comprehensive risk assessment model and emergency management capability assessment model for underground spaces based on the perspective of "human machine environment management" were constructed. A "scenario response" emergency decision-making model and an agile governance collaborative system were proposed. In terms of key technology research and development, we have broken through technical bottlenecks such as cloud based elastic architecture, multimodal data fusion, and BIM/CIM lightweighting, and developed a full lifecycle refined management platform that integrates intelligent travel guidance, accurate simulation of waterlogging risks, and multi-dimensional visualization analysis. The platform has achieved intelligent optimization of travel guidance, dynamic warning of waterlogging, and 3D visualization decision support in the demonstration application at the National Convention and Exhibition Center (Shanghai), significantly improving the efficiency of spatial management and emergency response capabilities during large-scale events, and providing innovative solutions for the sustainable development of underground spaces in mega cities.

Keywords: underground space, refined control, building information model, city information model

1. INTRODUCTION

With the acceleration of China's new urbanization process, the scale of urban underground space development continues to expand. By the end of 2023, a total of 3.276 billion square meters of urban underground space had been built across the country[1], with an additional 1.07 billion square meters added during the 13th Five-Year Plan period, and a development investment of 8 trillion yuan. Underground space has formed a multi-form infrastructure system including pipelines, transportation, civil defense, etc., and has become an important carrier for the safe operation of the city. However, the rapid expansion has led to the lack of resilience of underground space and the lack of multi-department collaborative management mechanism, and it is urgent to build a refined governance system for the whole life cycle.

Taking the National Exhibition and Convention Center (Shanghai) as a demonstration case, this study constructs a comprehensive risk assessment model of underground space from the four-dimensional perspective of "man-machine-environment-management" (personnel-facilities-equipment-environment-management), and integrates the risk matrix method, analytic hierarchy process-fuzzy comprehensive evaluation method to achieve quantitative analysis of multi-source risk factors. A multi-subject collaboration mechanism based on agile governance theory is innovatively proposed. Build a full-chain management system that includes emergency

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capability assessment and scenario response decision-making model. At the level of technology research and development, breakthroughs have been made in the three core technology groups, including the research and development of an IoT (Internet of Things) sensing system that supports cloud-based elastic architecture and multi-protocol adaptation, the construction of an intelligent diagnosis platform for cross-temporal and spatial data fusion, and the development of a three-dimensional visual decision-making system based on Building Information Modeling (BIM)/City Information Model (CIM).

The smart platform built in the application demonstration stage integrates technologies such as the Internet of Things, GIS, and artificial intelligence, and significantly improves the efficiency of facility operation and maintenance and emergency response capabilities through data linkage and system integration, providing replicable solutions for the refined and intelligent management of urban underground space.

2. THE CURRENT SITUATION AND CHALLENGES OF THE DEVELOPMENT OF DIGITAL AND INTELLIGENT INTEGRATION OF UNDERGROUND SPACE

2.1. Policy support and technical pathways

At the national level, promote the digital transformation of urban underground space through multi-dimensional policies. The "13th Five-Year Plan for the Development and Utilization of Urban Underground Space" and the guidance of the Ministry of Housing and Urban-Rural Development clearly put forward the goal of achieving full coverage of the comprehensive management information platform by 2025. The CIM Basic Platform Technical Guidelines and the Outline of the Construction of Real 3D China construct a 3D digital space foundation and provide a unified technical framework for underground space development[2,3].

The digital application system of the whole life cycle includes three stages: planning and design, construction management, and monitoring and operation and maintenance [4]. In the planning and design stage, BIM+GIS technology realizes 3D visualization of geological information, and cross-section partition stitching modeling and multidimensional dynamic analysis technology significantly improve the design accuracy. In the construction management stage, the 3D digital disclosure system reduces the rework rate, and the intelligent equipment collects data in real time to ensure construction safety. In the monitoring and operation and maintenance stage, drones, optical fiber sensing and other technologies build a cloud data collection system.

At present, there are three major trends in technology convergence: 5G IoT enables real-time perception of underground space, digital twin technology builds a virtual mirror system, and intelligent algorithms improve the accuracy of risk prediction [5]. In the future, it is necessary to break through the bottlenecks of unified data standards, cross-departmental collaboration, and security assurance.

2.2. Application scenarios and bottlenecks

The current core application scenarios of BIM technology include [6,7,8,9]:

1. Construction of scientific planning system: Through the integration of underground pipe network, existing buildings and geological data, a three-dimensional visual decision-making model is constructed to achieve pre-research and comparison of multiple schemes. With the help of parametric design and high-simulation simulation, the spatial layout and structural form are optimized, and the transformation of underground space planning from empirical decision-making to data-driven is promoted.

2. All-discipline collaborative design: Establish an interactive mechanism for multi-discipline BIM models such as buildings, structures, and equipment, and develop standardized design processes. Through data verification and model integration, the accurate transmission of design results at each stage is ensured, and the collaborative design efficiency of complex underground projects is significantly improved.

3. Construction life cycle management:

(1) Intelligent review system: realize digital delivery, intelligent verification and authority management

(2) 4D construction simulation: dynamic optimization of resource allocation and construction plan rehearsal

(3) Visual supervision: real-time monitoring of progress and three-dimensional layout of the construction site

(4) Completion management: Establish a digital file system through model comparison and analysis and correlation with acceptance data

4. Smart platform operation and maintenance:

(1) Space management: concealed engineering visualization and maintenance process simulation

(2) Monitoring and early warning: integrated sensors to achieve real-time monitoring of the environment and equipment status

(3) Emergency management: disaster scenario simulation and intelligent planning of evacuation paths

In terms of the bottlenecks and challenges of professional integration development, they mainly include[10,11]:

1. Deficiencies in the institutional system: the definition of underground space ownership and management rights is vague, there is a lack of unified management standards, and the legal subject of data ownership is not clear, which restricts the efficiency of resource integration and development.

2. Weak data foundation: there is a lack of systematic system for underground facilities and geological surveys, data is scattered and the update is lagging behind, and the cross-departmental coordination mechanism has not yet been established, forming an information island.

3. Limitations of technology application: the development of domestic core modeling software is lagging behind, the compatibility standard is missing, the digital twin technology has not yet achieved full life cycle coverage, and the maturity of special analysis tools for underground environment is insufficient.

In the future, with the in-depth development of the digital economy, BIM technology will be deeply integrated with digital twins, AI, IoT, etc., to build a complete industrial chain covering planning, design, construction, operation and maintenance. Promote the improvement of legislation and the unification of standards through policies, accelerate the digital transformation of underground space, and achieve efficient allocation and sustainable development of resources.

3. IN THE CONTEXT OF DIGITAL INTELLIGENCE, COMPREHENSIVE RISK MANAGEMENT AND CONTROL TECHNOLOGY FOR MULTI-COMPLEX AND LARGE-SCALE UNDERGROUND SPACE AND MULTI-SUBJECT COLLABORATIVE GOVERNANCE SYSTEM

The closed, systematic, and complex nature of underground space exposes it to multiple risks such as natural disasters, equipment failures, and human errors [12]. Based on the analysis framework of the "human-machine-environment-management" system, this paper provides innovative solutions for improving urban safety and resilience by constructing a theoretical system of underground space risk management and control [13]. The instructions are as follows:

3.1. Construction and application of comprehensive risk assessment model for underground space

3.1.1. Design of four-dimensional risk indicator system

In this study, the Delphi method and field investigation were used to construct a four-dimensional evaluation system including physical attributes, operating status, safety management, and environmental factors. The physical property dimension covers five indicators, such as structural durability (such as concrete carbonization depth) and seismic grade. The running status dimension includes three dynamic indicators, such as equipment failure rate and intelligent sensing device coverage. In the dimension of safety management, 6 system indicators such as the completeness of emergency plans and training coverage are set; Two natural indicators, such as groundwater level and land subsidence, were included in the dimension of environmental factors. The weight of each index was determined by analytic hierarchy process, in which the equipment failure rate and land subsidence degree were the key risk factors. Table 1 shows the indicators for assessing the comprehensive risk possibility of underground space.

Table 1. *Comprehensive Risk Probability Assessment Indicators for Underground Space*

First-level indicator （P_i）	**Weight of first-level indicator**（W_i）	**Second-level indicator** （P_{ij}）
physical property （P_1）	W_1	Construction time of facilities and equipment （P_{11}）
		Defects in facility and equipment design （P_{12}）
		Ground activity situation （P_{13}）
		Occupation of buildings （P_{14}）
		Facility and equipment setup （P_{15}）
running state （P_2）	W_2	Integrity level of facilities and equipment （P_{21}）
		Intelligent perception device （P_{22}）
		Daily operation and maintenance （P_{23}）

safety management（P_3）	W_3	Management system（P_{31}）
		Emergency plan（P_{32}）
		Professional competence of personnel（P_{33}）
		Guarantee funding situation（P_{34}）
		Suitable for teaching exercises（P_{35}）
		Information system（P_{36}）
environmental impact（P_4）	W_4	Degree of ground subsidence（P_{41}）
		Possible occurrence of severe weather conditions（P_{42}）

3.1.2. Risk matrix and AHP-FCE integrated assessment method

Innovative use of AHP-FCE method and risk matrix method to evaluate the comprehensive risk of underground space.

Through the analytic hierarchy process, the weight of the probability index is assigned, and the probability score *P* of the comprehensive risk of underground space is obtained. The formula for assessing the potential for comprehensive risk of underground space is as follows:

$$P=\sum_{i=1}^{4}(W_i(\sum_{j=1}^{n}W_{ij}P_{ij})) \tag{1}$$

Among them, W_i is the weight of the first-level indicator, W_{ij} is the weight of the second-level indicator, and P_{ij} is the score of the second-level indicator.

Through the analytic hierarchy process, the weight of the consequence index is assigned to the consequence score of the comprehensive risk of underground space *C*. The formula for assessing the comprehensive risk and consequences of underground space is as follows:

$$C=\sum_{i=1}^{4}W_iC_i \tag{2}$$

Among them, W_i is the weight of the first-level index, and C_i is the score of the first-level index.

According to the probability and consequences of the occurrence of risk factors in underground space, the risk level is determined by drawing a risk matrix map.

The formula for the risk value of risk factor *i* for underground space is:

$$R_i=f(P_i,C_i)=P_i*C_i \tag{3}$$

Taking a subway transfer station as an example, through 10 years of historical data statistics, the calculated risk value of facility aging is R=3.2（P=2.8, C=1.1）, which is at the level II risk level. Combined with Monte Carlo simulation technology, the probability of high-risk events in the next five years is predicted to be 12.3%, which is 27% more accurate than the traditional method.

3.1.3. An empirical study on the risk assessment of rainstorm disasters

Taking an underground space in Shanghai as the research object, a spatial risk matrix containing 12 evaluation units was constructed. The results show that the risk level of the low-lying area reaches level I, and mobile drainage units need to be configured. The underground garage has a risk level of III, which can be reduced to level IV by optimizing the drainage system. This study provides accurate data support for urban flood control planning, and promotes the establishment of a "red, yellow and blue" three-color early warning mechanism.

3.2. Innovation of underground space emergency management capacity assessment system

3.2.1. Six-dimensional competency assessment framework

Based on the ISO 22301 standard, a six-dimensional evaluation system including organization and management, risk prevention and control, monitoring and early warning, emergency response, recovery and reconstruction, and public participation is constructed. An evaluation scale containing 32 third-level indicators was developed, and the entropy weight method was used to determine the weights, in which monitoring and early warning ability and cross-departmental coordination were the core capability dimensions. Figure 1 shows the index system for the evaluation of underground space emergency management capacity.

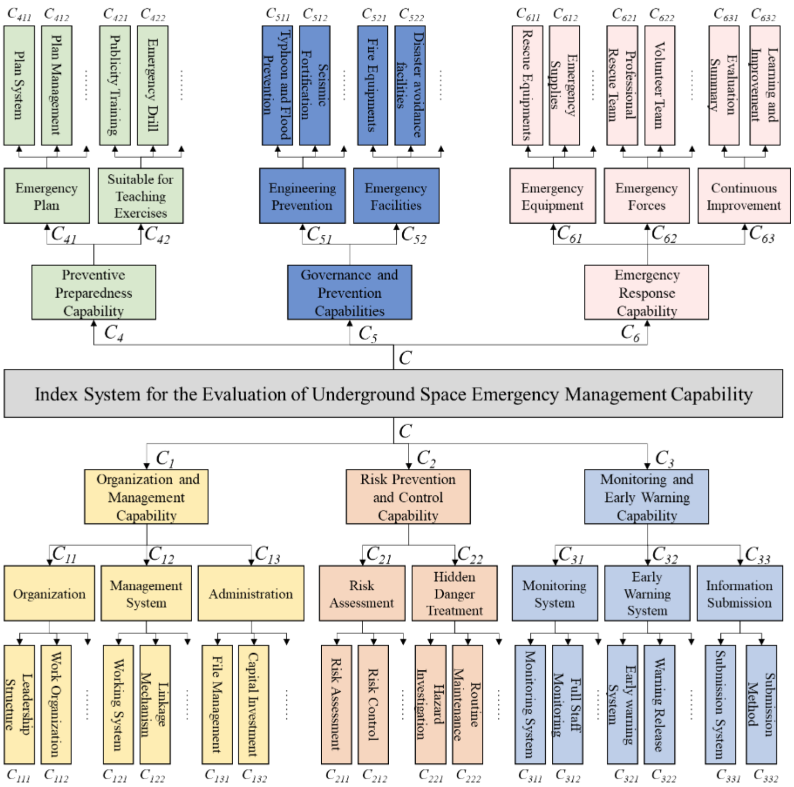

Figure 1. *Evaluation index system of underground space emergency management capacity*

3.2.2. Construction of underground space emergency management capacity assessment model

According to the evaluation index system, the evaluation formula for underground space emergency management capability is as follows:

$$M = \sum_{i=1}^{6} (\omega_i (\sum_{j=1}^{n} \omega_{ij} (\sum_{k=1}^{m} \omega_{ijk} M_{ijk}))) \tag{4}$$

Among them: ω_i is the weight of the first-level index, ω_{ij} is the weight of the second-level index, and ω_{ijk} is the weight of the third-level index; M_{ijk} is a three-level indicator score.

3.3. Construction of a multi-subject collaborative governance system

3.3.1. The multi-subject governance system of the International Exhibition Center

The multi-dimensional and complex system governance elements of the underground space of the International Exhibition Center from planning, construction, operation and service to emergency and disaster prevention are studied, and a multi-subject governance system of underground space is constructed [13], as shown in Figure 2.

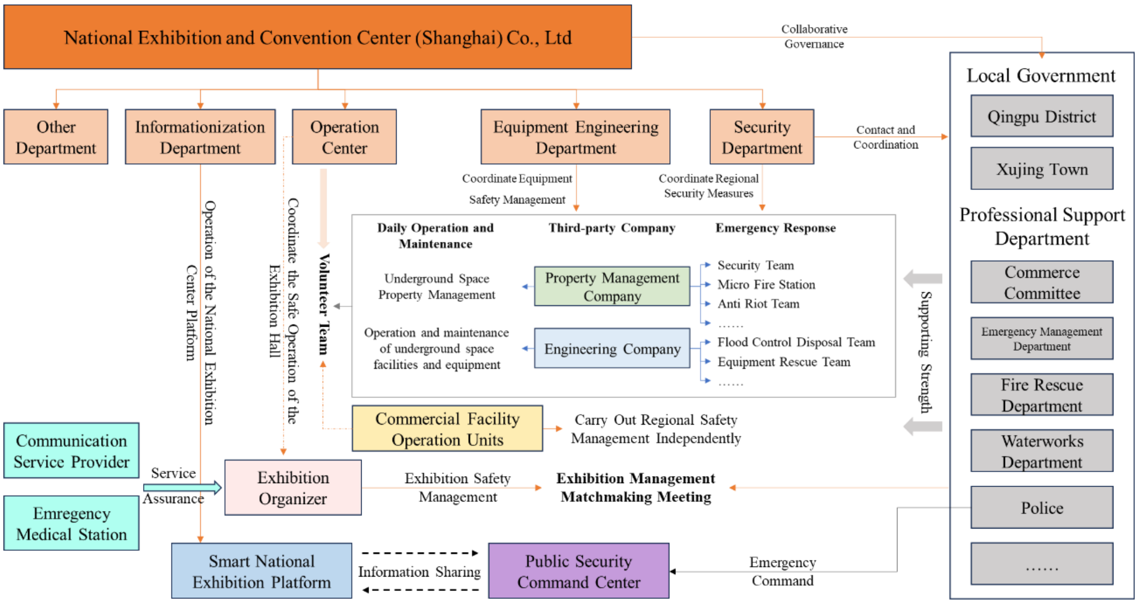

Figure 2. The multi-subject governance structure of the National Exhibition and Convention Center

Design a data link with event governance as the core, and form a response plan for the collaborative governance of multiple subjects in underground space. It is planned to communicate with the International Exhibition Center to further improve the content of the plan.

3.3.2. Agile governance mechanism innovation

Establish a closed-loop management mechanism of "monitoring, research, judgment, disposal, and evaluation", and rely on the CIM platform to achieve cross-departmental data sharing. In the management of the underground space in the International Exhibition Center and the surrounding area, the data of 8 departments, including water affairs, emergency response, and transportation, were integrated, and the risk response time was reduced from 1 hour to 15 minutes.

4. RESEARCH ON THE KEY TECHNOLOGIES OF THE WHOLE LIFE CYCLE FINE MANAGEMENT PLATFORM OF MULTI-COMPLEX FUNCTIONS AND LARGE-SCALE UNDERGROUND SPACE

Through the deep integration of IoT sensing, intelligent diagnosis and digital twin technology, a full-life cycle management platform for large-scale underground space with multiple complex functions is built, providing a new paradigm for urban safety and resilience construction.

4.1. Architectural innovation of IoT data ubiquitous access system

4.1.1. Elastic cloud-edge collaboration architecture:

The refined management system of the whole life cycle of multiple complex functions and large-scale underground space adopts the "cloud-edge-end" architecture. This is shown in the figure below.

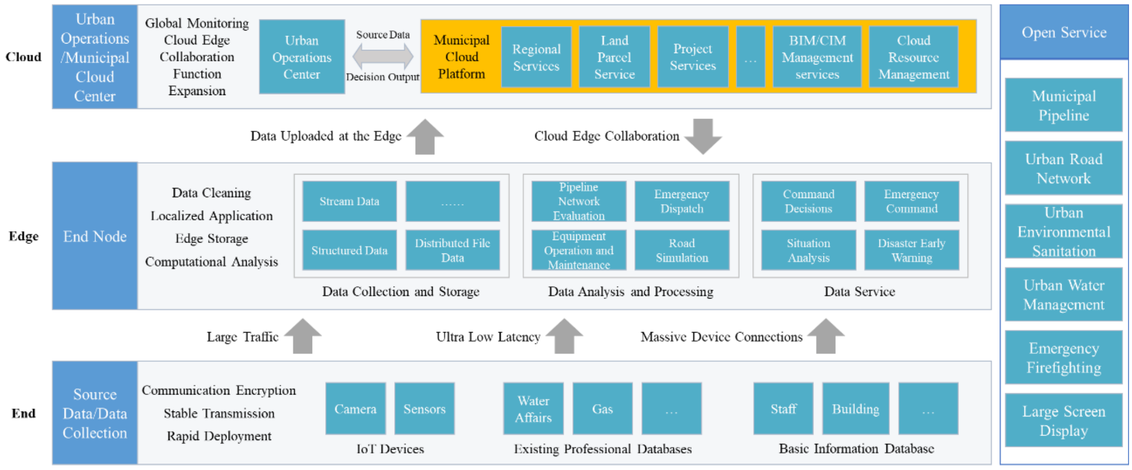

Figure 3. *Overall system architecture*

Through the "cloud-edge collaboration" mode, the tasks and interactions between the three levels are reasonably planned, and a large number of computing and processing work is placed at the edge, which reduces the pressure of data backhaul and data processing on the cloud platform, and at the same time reduces the coupling degree between various services, realizes resource deployment according to business needs, increases program running performance, and reduces the overall delay of data processing.

4.1.2. Multimodal protocol adaptation technology

Develop protocol conversion middleware to realize real-time conversion of industrial protocols such as RS485 and OPC UA and MQTT IoT protocol. The device access module supports the hybrid access of 2G/3G/4G, NB-IoT, LoRa, WiFi and other networks according to different data communication connection modes of IoT terminal equipment, so as to realize large-scale access to various types of terminal devices in the IoT sensing layer.

4.2. Algorithm breakthrough of intelligent diagnosis system

4.2.1. Martimodar beat him to Fucion Moder

The risk inference method and state intelligent diagnosis technology of municipal facilities based on multi-modal cross-spatiotemporal scale massive data include the following three aspects:

1. Improve the extraction of cross-temporal and spatial data information: The key features of historical time series data are analyzed by feature extraction technology, and the data sparsely distributed in geographic space is further supplemented based on expert knowledge. It is mainly used to solve the problems of incomplete raw data information and serious noise interference.
2. Multimodal data fusion analysis and utilization: The microservice analysis module with distributed characteristics is used to process multi-modal data in different scenarios. This process can be combined with some non-professional data, such as considering holidays, meteorological and other data, to assist in data prediction.
3. Iterative optimization based on massive data: Based on the machine learning model, the operation status analysis algorithm of municipal facilities is constructed, and the model is continuously trained and updated with massive data to realize its iterative optimization ability. It can realize trend prediction of massive data over a long period of time.

4.2.2. Microservice-based intelligent applications

12 independent microservice modules are developed, and each module opens API interfaces for front-end access, which ensures the scalability of the system, and has the characteristics of low coupling and strong reusability.

4.2.3. Predictive maintenance systems

An equipment health assessment model based on digital twins was constructed to improve the predictive maintenance coverage and reduce the equipment failure rate in the wind turbine monitoring of an underground parking lot in Shanghai. The system dynamically optimizes maintenance strategies through reinforcement learning, saving a lot of O&M costs every year.

4.3. BIM/CIM-driven emergency response platform construction

4.3.1. BIM/CIM-driven spatiotemporal big data engine

Developed distributed 3D spatial index technology to support second-level loading of 100GB BIM models. In the underground space project in Qianhai, Shenzhen, the smooth browsing of 2 million square meters of models was realized. The rendering optimization algorithm developed based on the OpenSceneGraph engine stabilizes the frame rate of complex scenes at more than 60 fps.

4.3.2. Digital twin emergency deduction

A digital twin of underground space containing hundreds of dynamic parameters was constructed to accurately predict the smoke diffusion path in the fire simulation of an underground transportation hub in Shanghai, and guide the optimization of the design of three evacuation channels. Monte Carlo simulations allow you to evaluate the effects of different contingency scenarios in less than 15 minutes.

4.3.3. Linkage disposal of multi-source information

Establish an intelligent response mechanism of "risk early warning, plan matching, and resource scheduling". The hierarchical response system for emergency response includes functions such as incident scale assessment, response level determination, and emergency resource allocation, as shown in Figure 4.

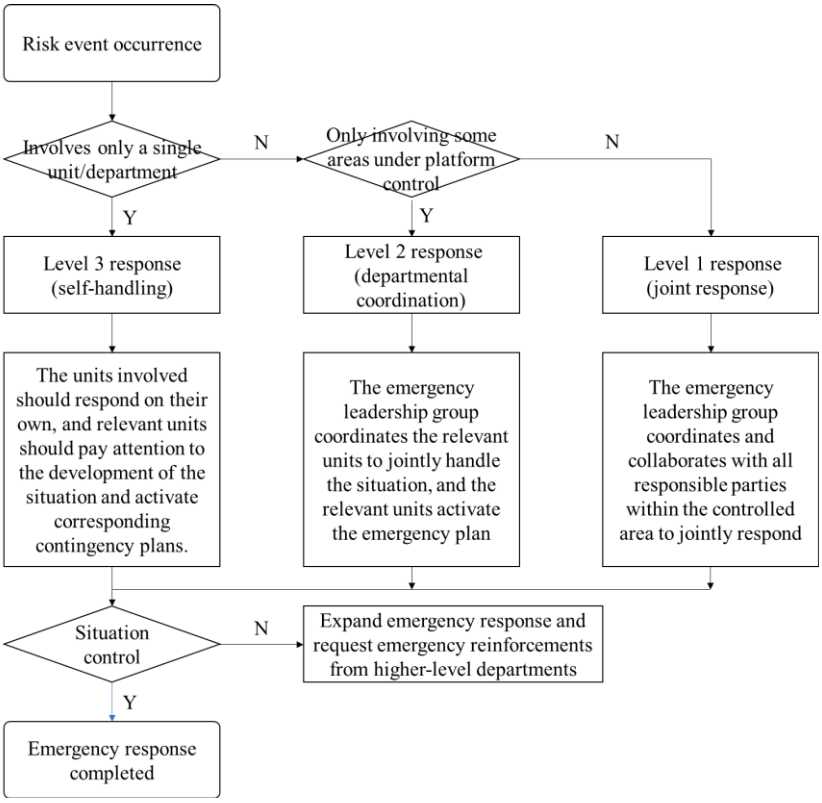

Figure 4. *Hierarchical response process for emergency response*

5. APPLICATION DEMONSTRATION: THE INNOVATIVE PRACTICE OF THE REFINED MANAGEMENT AND CONTROL SYSTEM OF THE NATIONAL EXHIBITION AND CONVENTION CENTER (SHANGHAI)

In today's accelerating urbanization, the underground space of super-large urban complexes has become the "lifeline" of urban operation. As the world's largest convention and exhibition complex, the underground space of the National Exhibition and Convention Center (Shanghai) carries the functions of traffic guidance, commercial operation and emergency support for tens of thousands of people per day. In 2023, the annual exhibition area will exceed 7 million square meters, accounting for more than 40% of Shanghai's total operating data, posing unprecedented challenges to the management of underground space. In the face of complex crowd dynamics, extreme weather threats, and facility operation and maintenance pressures, the traditional management model has been difficult to adapt to demand. In this context, the "National Convention and Exhibition Center and the Surrounding Underground Space Refined Management and Control System" came into being, and through the integration of multi-source data and cutting-edge technology, an intelligent solution for underground space governance was built.

5.1. Technical Architecture: a multi-dimensional integrated intelligence hub

With the core concept of "data-driven and intelligent decision-making", the system has built a technical architecture system of "one core and three wings". Its core lies in building a standardized data platform, integrating multi-source heterogeneous data from transportation, meteorology, municipal, security and other fields, and realizing real-time data processing through edge computing. The dynamic enhanced knowledge graph technology endows the system with self-learning ability, which can automatically associate data from different fields to form a digital twin model of underground space operation. The containerized microservice architecture ensures the scalability and flexibility of the system and supports the rapid iterative upgrade of functional modules.

Three core modules constitute the "three wings of wisdom" of the system: Through the integration of 2.5D indoor maps and 3D outdoor models, the smart travel module realizes centimeter-level positioning and navigation; Based on the two-dimensional linkage simulation technology, the waterlogging risk module constructs a digital sand table of the urban drainage system. The Visual Analytics module uses a real-time rendering engine to transform complex data into intuitive and easy-to-understand 3D scenes. This architecture design not only meets the current management needs, but also reserves the technical interface for future expansion.

5.2. Functional innovation: intelligent upgrade of underground space management

5.2.1. Smart Mobility: From Passive Guidance to Proactive Optimization

The system breaks through the limitations of the traditional static identification system and builds a dynamic navigation service system. Through real-time simulation analysis of the evacuation of large passenger flow of the exhibition, combined with dynamic guidance, seamless above-ground and underground navigation is realized. In the 2024 auto show test, the system predicts the exit pressure of the subway station through the passenger flow simulation model, and dynamically adjusts the channel opening strategy, so that the crowd density in key areas is greatly reduced.

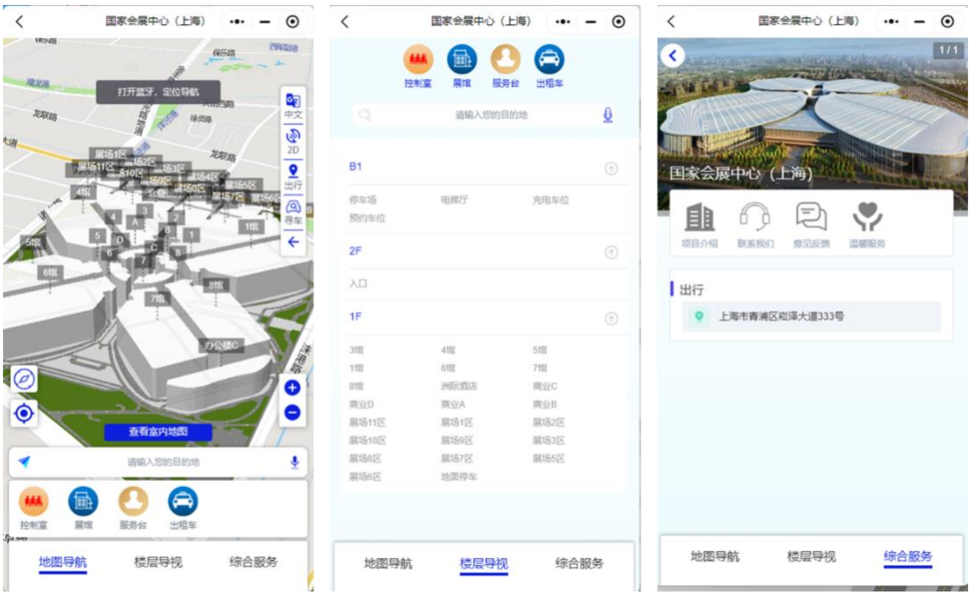

Figure 5. *Smart mobility applet*

5.2.2. Waterlogging prevention and control: from emergency response to risk pre-control

In view of the frequent extreme weather in the Yangtze River Delta region, a full-chain prevention and control system of "monitoring-simulation-early warning-disposal" has been systematically constructed. In the inversion of the "7 • 21" rainstorm in 2023, the error between the calculated water depth and the measured data was less than 5%, and 5 key water accumulation points were successfully located. Through the simulation of the 50-year rainstorm scenario, the system identifies three low-lying flood-prone areas, which provides a quantitative basis for the renovation of the pipe network. The intelligent scheduling algorithm can generate the optimal emergency plan within 10 minutes, which shortens the response time by 40% compared with the traditional mode.

Figure 6. *Simulation of waterlogging risk in the waterlogging risk module*

5.2.3. Visual decision-making: from data stacking to scenario insights

The 3D visualization platform integrates 12 types of dynamic data such as sunshine analysis, weather simulation, and human flow heat, and supports multi-dimensional scene switching. In foundation pit monitoring, the real-time linkage between BIM model and sensor data is used to achieve millimeter-level deformation early warning. The Flood Simulation Module dynamically demonstrates the process of water level rise and visualizes the difference in the effect of different flood control measures. This immersive, interactive experience enables managers to make scientific decisions quickly in extreme weather.

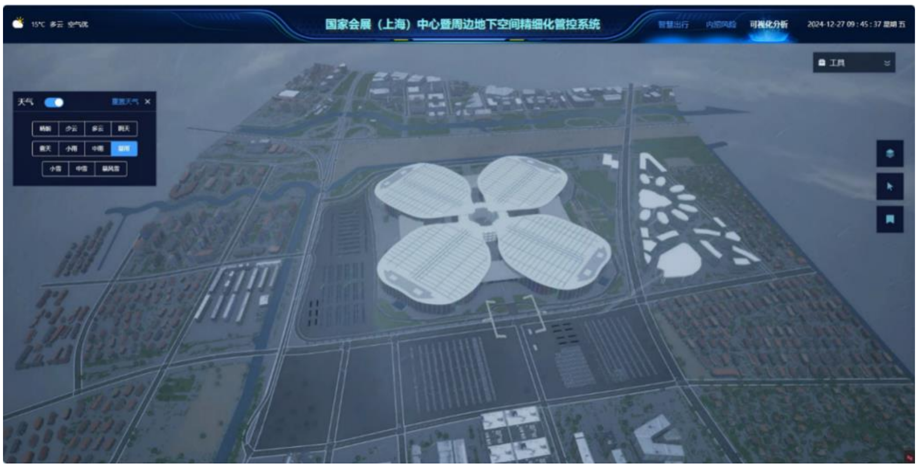

Figure 7. *The weather system simulates rainstorm weather*

5.3. Application results: from technological innovation to management change

Since its operation, the system has proven its value in multiple scenarios. In terms of safety and security, the early warning of waterlogging successfully predicted the process of heavy rainfall and avoided major economic losses. Significantly improved efficiency, smart travel shortens peak travel time, and parking lot turnover is accelerated; Optimized decision-making, assisted in the formulation of plans and reduced the duration of temporary traffic control; At the same time, it is green and low-carbon, and effectively saves energy consumption and reduces carbon emissions through intelligent linkage.

6. CONCLUSIONS

In this study, the National Exhibition and Convention Center (Shanghai) and the surrounding underground space are used as a pilot to carry out technical verification and form a replicable solution, including the establishment of technical standards for special scene monitoring, the realization of green and low-carbon operation management, and the verification of the applicability of the whole life cycle control technology in complex environments. The research value and innovation lie in constructing the theoretical system of underground space life cycle management, innovating the integration of multi-system collaborative governance and holographic perception technology, promoting the transformation of underground space management from passive response to active prevention and control, and providing standardized technical support for urban renewal. This study provides theoretical support and practical paradigm for the sustainable development of underground space in megacities, and the relevant results have been applied to the refined urban management of Shanghai, effectively improving the safety resilience and management efficiency of underground space.

In the future, we can further deepen the research on cross-regional data sharing mechanisms, explore the in-depth application of AI in complex scenarios, and promote the collaborative optimization of low-carbon technologies and intelligent management.

7. ACKNOWLEDGEMENTS

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8. BIBLIOGRAPHY

[1] Strategic Consulting Center of Chinese Academy of Engineering, Underground Space Branch of Chinese Society of Rock Mechanics and Engineering, & Underground Space Planning Branch of China Urban Planning Society (2024). “2024 Blue Book of China's Urban Underground Space Development.” Urban Planning Society of China. https://www.planning.org.cn/news/view?id=16315.

[2] Ministry of Housing and Urban-Rural Development of the People's Republic of China (2021). “The Ministry of Housing and Urban-Rural Development issued the Technical Guidelines for City Information Modeling (CIM) Basic Platforms (Revised Edition).” Chinese government website. https://www.gov.cn/xinwen/2021-06/14/content_5617553.htm.

[3] Ministry of Natural Resources of the People's Republic of China (2021). “Outline of Construction Technology of Real 3D China (2021 Edition)” The Paper. https://www.thepaper.cn/newsDetail_forward_14093637.

[4] Li J. (2024). Research on the whole process management of highway construction based on BIM technology. Volkswagen Standardization, 22, 148-150.

[5] Zeng S., Su D., & Gong H. (2025). Application and research progress of digital twin technology in the operation and maintenance stage of urban underground space. Tunnel Construction, 1, 57-76.

[6] Ma Y., Yang J., & Cheng R. (2024). Application of BIM technology in construction of building engineering. Popular Science, 10, 44-46.

[7] Cai M. (2022). Research on the Application of BIM Technology in Urban Underground Space Management. China Construction Informatization, 18, 73-75.

[8] Guan X. (2016). Discussion on the Planning of Underground Space in Smart City Based on BIM Concept. Sichuan Building Materials, 42(8), 64-65.

[9] Su X., Cai H., & Guo D. (2014). Application of BIM technology in urban underground space development. Journal of PLA University of Science and Technology (Natural Science Edition), 15(3), 219-224.

[10] An W. (2022). Discussion and Reflection on the Digitization Path of Urban Underground Space Elements: A Case Study of Shanghai. Shanghai Land & Resources, 43(2), 107-112.

[11] Yang H., Jiang Y., & Li Z. (2021). Research on the development strategy of comprehensive management of underground space development. Strategic Study of Chinese Academy of Engineering, 23(4), 126-136.
[12] She L. (2017). Urban Comprehensive Disaster Prevention and Underground Space Risk Early Warning Management. Urban and Rural Development, 12, 59-61.
[13] Shanghai Municipal Engineering Design & Research Institute (Group) Co., Ltd., & School of Social Development and Public Policy, Fudan University. (2024). “Digital Intelligence Empowers the Development and Utilization of Underground Space in Megacities”. Scientific Research Project of Shanghai Municipal Commission of Housing and Urban-Rural Development.