

Research on Management Models and Key Technologies of Urban Integrated Utility Tunnels

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Abstract

As a typical urban lifeline infrastructure, integrated utility tunnels play a crucial role in enhancing urban operational safety, optimizing spatial environments, and improving carrying capacity. This paper systematically reviews domestic and international management models of integrated utility tunnel construction, compares their advantages, disadvantages, and applicable conditions, and analyzes the key factors influencing model selection. On the technical side, construction methods, performance design, and the application of information technologies such as BIM and GIS are investigated. In response to challenges including incomplete policies and regulations, high construction and operation costs, and complex system management, optimization strategies are proposed: in terms of management, the promotion of PPP models, corporatized operation, and property-based management with a paid-use system; in terms of technology, strengthening intelligent monitoring and early warning, BIM integration, and pipeline information platforms; in terms of policy, improving the regulatory framework, reinforcing technical standards, and enhancing public awareness to create a favorable environment for tunnel construction and operation.

Keywords

Urban integrated utility tunnel, construction management model, key technology, PPP model, BIM, GIS, policy and regulation.

1. Introduction

Gas leakage accidents are generally caused by the formation of leakage holes in gas pipes due to rust, impact and other reasons. The type of gas leakage studied in this article is small hole leakage. Small hole leakage refers to the gas leakage process where the diameter of the leakage hole is less than 20mm. Due to the small hole diameter, when there are no tributaries or other leakage holes above the leakage opening, if the friction loss and along-the-way resistance loss of the gas pipeline are not taken into account, the gas leakage flow at this time is relatively large. The following assumptions are made regarding the leakage process of the small hole:

With the acceleration of urbanization and continuous population growth, the demand for urban infrastructure has been steadily increasing. As aboveground space becomes saturated, the development and utilization of underground space has emerged as a critical direction in urban construction. Among these efforts, the construction of urban integrated utility tunnels—as a typical urban lifeline project—not only saves land resources but also improves the efficiency of infrastructure construction and maintenance. This contributes significantly to achieving efficient, intelligent, and sustainable urban development.

In recent years, supported by national policies and government initiatives, the construction of integrated utility tunnels in China has grown rapidly, with continuous expansion in investment scale and industry development. However, such projects still face significant challenges,

including high engineering complexity, considerable construction and operation costs, and substantial management difficulties [1–2].

Therefore, systematically reviewing domestic and international management models and key technologies, summarizing their characteristics and applicable conditions, and exploring the critical factors influencing model selection are of both theoretical and practical importance for improving the level and efficiency of integrated utility tunnel construction in China [3–4]. Based on international experience, this paper reviews the current key technologies of utility tunnel construction, analyzes the main challenges faced in China, and proposes targeted optimization strategies to promote sustainable development of urban utility tunnels.

2. Analysis of Management Models for Urban Integrated Utility Tunnel Construction

2.1. Comparison of International Management Models

Globally, integrated utility tunnels have been most successfully developed in Europe, Japan, and Singapore [5]. Each country and region has formed distinctive development models, which can be summarized as the Japanese model that combines roadway departments with management regulations, Singapore's "full life-cycle" management model, and France's parliamentary hearing system [6].

(1) Japanese Model

Japan is a global leader in terms of both the scale and technical advancement of utility tunnel construction, where the tunnels are referred to as "kyōdōkō" (common trench) [7]. The Great Kanto Earthquake of 1923 severely damaged underground pipelines and prompted the Tokyo government to launch pilot projects in 1926 to prevent repeated excavation of roadways. Since then, a series of laws such as the Special Measures Law for the Construction of Common Trenches and the Deep Underground Utilization Law were enacted to facilitate tunnel development. By 2015, nearly 80 cities including Tokyo, Osaka, Nagoya, Yokohama, and Fukuoka had built more than 2,057 km of tunnels, making Japan the world's largest and most advanced utility tunnel system.

Japan's experience can be summarized as: ① Clear land ownership system-the government can expropriate land for public use with compensation, avoiding property disputes; ② Diversified financing sources-construction costs are jointly borne by the government, road corporations, and utility companies, with a dedicated fund established to ensure stable financing; ③ Comprehensive government supervision-the Ministry of Land, Infrastructure, Transport and Tourism oversees planning, investment, inspection, and operation, supported by expert committees to ensure transparency and rationality.

(2) Singapore Model

Singapore began constructing its first utility tunnel at Marina Bay in the late 1990s, which was the first "manned" full life-cycle tunnel in Asia [8]. Its management model is characterized by: ① Full life-cycle management-covering planning, construction, operation, and maintenance, ensuring long-term sustainability [9]; ② Organizational coordination-the Urban Redevelopment Authority supervises and enforces quality standards, the Ministry of National Development provides financing, CPGFM Pte. Ltd. manages facilities and charges, while utility operators manage their own pipelines; ③ Cost-sharing mechanism-the government funds construction, while operation and maintenance costs are shared among utility companies through fixed charges (based on spatial usage) and variable charges (based on consumption); ④ Efficient regulation-quality control is strictly enforced by the Urban Redevelopment Authority, while CPGFM ensures transparent and reasonable charging practices.

(3) French Model

In France, the operation and maintenance of utility tunnels are managed directly by the government. Its main characteristics include: ① Public good orientation-utility tunnels are regarded as public infrastructure, with government assuming full responsibility. Paris established a Sewer Management Bureau dedicated to tunnel operation and maintenance, while district governments manage tunnels within their jurisdictions. ② Autonomous management-the government owns both the property rights and operational responsibilities, receiving income while bearing costs. ③ Multiple financing channels-maintenance costs are covered through entry fees and financial subsidies, with rental fees determined by local councils through public hearings, ensuring fairness between public interest and utility companies.

A comparative analysis of international management models is summarized in Table 1.

Table 1. Comparison of management modes of pipeline corridor construction abroad

Country	Management Mode	Organizational Structure
Japan	Clear land ownership system; diversified funding sources; comprehensive government regulatory system	Road administrators in charge; pipeline divisions supervise; specialized companies handle O&M
Singapore	Administrative authorities supervise with re-bidding every three years; government grants O&M units authority for charging and maintenance; O&M units compile management manuals	Ministry of National Development as project owner; Urban Redevelopment Authority as regulator; CPGFM team responsible for O&M

2.2. Omparison of Domestic Management Models

(1) Taiwan Region

Taiwan's utility tunnel development has drawn heavily on Japanese experience and has gradually established a relatively complete management system [10]. Its main features include: ① Government leadership with legislative support-the government plays a leading role in planning and implementation, supported by dedicated legislation; ② Specialized management agencies-major cities have established dedicated utility tunnel management authorities responsible for planning, construction, financing, and regulatory enforcement, thereby ensuring unified and efficient management; ③ Dedicated funding mechanisms-a special fund is created for utility tunnel construction, with strict legal supervision of fund allocation and usage to enhance efficiency and transparency; ④ Comprehensive regulatory framework-detailed rules cover charging standards, usage permits, maintenance regulations, and public disclosure requirements, ensuring standardized operation; ⑤ Clear cost-sharing arrangements-laws specify a fair distribution of costs between government and utility companies, balancing governmental control with enterprise affordability. Overall, the Taiwan model highlights government dominance, legal frameworks, and funding transparency, ensuring steady advancement and safe operation of utility tunnels.

(2) Mainland China

At present, two main construction and management models prevail in mainland China: government-funded projects and public-private partnership (PPP) projects [11]. Under the government-funded model, the government fully finances and constructs utility tunnels, while utility companies either rent or use the space free of charge to install pipelines. Upon completion, the facilities are typically transferred to state-owned enterprises for operation and management. For example, the Guangzhou University Town utility tunnel was financed and built by the government and later handed over to a local investment company for management. The other approach is the equity cooperation model, in which government-owned asset management companies collaborate with private capital to establish joint-stock project companies. These companies adopt enterprise-style management, covering investment,

construction, and operation. This model alleviates government fiscal burdens, introduces professional management and advanced technology, and enhances operational efficiency, thereby achieving mutual benefits for both government and enterprises.

A comparative summary of domestic management models is provided in Table 2.

Table 2. Comparative Analysis of Domestic Utility Tunnel Management Modes

Region	Management Mode	Organizational Structure
Taiwan	Government guidance and legislation-driven model	Utility Tunnel Management Authority responsible for planning, construction, funding allocation, and enforcement; establishment of a dedicated construction fund with earmarked use; comprehensive regulations and systems formulated by all levels of government
Mainland China	Two modes: full government funding and public-private partnership (PPP)	Under the full government funding mode, the government and state-owned enterprises play a dominant role; under the joint-stock cooperation model, government, state-owned enterprises, and private capital jointly establish and manage the project company

2.3. Factors Influencing the Choice of Management Model

The choice of construction and management models for integrated utility tunnels should consider multiple dimensions, including urban characteristics, economic conditions, legal frameworks, and management capacity, to ensure scientific decision-making and local adaptability. The main influencing factors are as follows:

- (1) Urban scale and development stage
- Population density, pipeline demand, and development stage directly affect model selection. Large cities, with concentrated demand, are more suited to unified planning and centralized construction, while medium- and small-sized cities may adopt decentralized or partially centralized models. Newly developed districts or old city renewal projects often offer better opportunities for unified planning and integrated construction.
- (2) Economic conditions and fiscal capacity
- The enormous capital investment required for utility tunnel construction makes the level of economic development and fiscal capacity decisive. Cities with strong financial resources can adopt government-led investment, whereas those with limited budgets should introduce private capital through PPP models. In addition, pricing and revenue mechanisms must be carefully designed to ensure financial sustainability.
- (3) Legal and policy environment
- Utility tunnel construction involves multiple sectors and stakeholders, requiring a sound legal and policy framework. Comprehensive legislation should clarify the rights and responsibilities of all parties, regulate construction and operation, and provide supportive policies such as land allocation, tax incentives, and financial subsidies. Effective interdepartmental coordination and streamlined approval procedures are also essential to enhance implementation efficiency.
- (4) Geographical conditions and construction difficulty
- Topography, geological structure, and the complexity of existing pipelines significantly influence construction difficulty and costs. In areas with complex geology or dense pipeline networks, decentralized or partial construction may be more practical, whereas in favorable conditions, centralized construction is preferable. In addition, the impact on traffic and urban landscapes must be carefully assessed to minimize disruption.
- (5) Operation management and technical capacity
- Utility tunnel operation is a long-term and complex system engineering project requiring professional teams and advanced technologies. Cities should evaluate their management

capacity and technical resources before selecting an appropriate model, whether direct government management, outsourcing to professional firms, or establishing dedicated agencies. The adoption of intelligent and digital management technologies should also be encouraged to enhance safety, reliability, and operational efficiency.

In summary, the selection of utility tunnel management models must comprehensively weigh urban scale, economic capacity, policy and legal frameworks, geographical conditions, and management capabilities to identify an optimal solution tailored to local realities, thereby promoting the high-quality development of urban infrastructure.

3. Key Technologies in the Construction of Urban Integrated Utility Tunnels

3.1. Construction Technologies

The main construction methods for urban integrated utility tunnels include cut-and-cover with cast-in-place concrete, cut-and-cover with prefabricated assembly, and tunneling methods, as shown in Figure 1. The cast-in-place method is mature and well-established, but its disadvantages include long construction cycles and significant impacts on the surrounding environment. The cut-and-cover prefabricated method improves quality control through factory-based production, while tunneling methods are better suited for congested areas where ground-level construction is constrained.



Figure 1. Construction methods for urban integrated utility tunnels

In recent years, with the expansion of tunnel construction and the increasing complexity of geological conditions, a series of new construction technologies have emerged, including dual-mode shield tunneling with prefabricated assembly, mobile shield tunneling with prefabricated assembly, and U-shaped shield tunneling with prefabricated assembly. Each of these methods demonstrates specific advantages in construction organization, applicable scenarios, and efficiency (as shown in Table 3).

Comparative analysis indicates that prefabricated assembly technology effectively addresses the limitations of traditional cast-in-place methods, such as long duration, low flexibility, and high environmental disruption. Its key advantages include: ① Quality control-standardized factory conditions ensure stable component quality, reducing on-site uncertainties; ② Shortened construction period-the combination of factory prefabrication and on-site assembly accelerates progress; ③ Environmental friendliness-on-site disturbance and environmental pollution are significantly reduced. For these reasons, prefabricated assembly has become the mainstream approach in many urban infrastructure projects. The following sections will further elaborate on its core processes and application prospects.

Table 3. Analysis and comparison of several integrated pipe corridor construction technologies

Construction Technique		Characteristics	Process Workflow	Advantages	Disadvantages
Traditional Methods	Cut-and-cover cast-in-place	Simple and straightforward construction process with strong controllability; suitable for favorable geological conditions and small-scale projects	Excavating trenches, followed by cast-in-place reinforced concrete frame construction, and finally pipeline installation	Simple construction, relatively low cost	Long construction period, significant impact on traffic, unsuitable for areas with high groundwater levels or complex geology
	Cut-and-cover prefabricated assembly	Prefabricated components used for assembly; fast construction speed with relatively minor traffic disruption; suitable for relatively stable geological areas	Prefabricated sections are manufactured in advance, then assembled on-site, followed by pipeline installation	Fast construction, short duration, less traffic disruption	Requires prefabrication yard, high transportation costs, unsuitable for areas with uneven terrain
	Tunneling method	Applicable in complex geological conditions or high groundwater areas; minimal surface traffic impact but high technical difficulty and cost	Typically uses shield tunneling or mining methods; excavation carried out by tunneling machines or blasting, followed by tunnel structure construction and pipeline installation	Minimal impact on surface traffic; suitable for complex geology and high groundwater areas	High technical difficulty, high cost, long construction period
New Methods	Dual-mode TBM prefabricated assembly	Uses dual-mode tunnel boring machine (TBM) combined with prefabricated assembly to improve efficiency and reduce costs	Dual-mode TBM enables both excavation and prefabricated tunnel segment assembly, optimizing workflow	High efficiency, low cost, short construction cycle	Requires specialized dual-mode TBM equipment; high technical requirements
	Mobile shield machine prefabricated assembly	Employs mobile shield machine combined with prefabricated assembly, improving safety and reducing environmental impact	Mobile shield machine precisely controls excavation while assembling prefabricated tunnel structures in place	High safety, minimal environmental impact, suitable for construction in urban core areas	High equipment cost, requires specialized personnel

At the current stage, according to the degree of prefabrication of materials and components[12], prefabricated assembly utility tunnels can be classified into four categories: fully prefabricated concrete tunnels, semi-prefabricated concrete tunnels, steel tunnels, and new-material tunnels[13].

(1) Fully Prefabricated Concrete Utility Tunnels

Fully prefabricated concrete utility tunnels are systems in which all structural components—such as pipelines, drainage channels, cable troughs, and ventilation ducts—are manufactured in factories and then transported to the site for assembly. Compared with conventional on-site construction, this approach offers significant advantages: rapid construction speed, reliable quality control, and reduced environmental disturbance, thereby improving both efficiency and sustainability of infrastructure projects.

According to the form of cross-sectional joints, fully prefabricated utility tunnels can be classified into three types, as shown in Figure 2:

① Whole-section prefabricated assembly (a)

Entire tunnel segments, typically several meters long, are prefabricated in factory settings and then transported for on-site installation. This approach is analogous to “assembling building blocks,” minimizing on-site work while ensuring consistent quality. Its strengths include high efficiency, low on-site labor demand, and enhanced safety. However, it imposes strict requirements on transportation and lifting conditions. It is most suitable for urban trunk roads with heavy traffic, strict time constraints, and high safety standards.

② Segmental block prefabricated assembly (b)

In this method, the tunnel is divided into smaller blocks or segments, which are individually prefabricated and then sequentially assembled on site. This “modular” approach improves transportability and flexibility, making it suitable for areas with uneven geology, dense pipeline networks, or limited space. The trade-off is a relatively higher on-site workload compared with whole-section assembly.

③ Multi-compartment prefabricated assembly (c)

Here, each tunnel unit is produced as an independent compartment, customized for specific functions such as electricity, telecommunications, or water supply. By combining multiple compartments with standardized interfaces, a multifunctional tunnel can be built on site. This method provides high adaptability, scalability, and functional integration, making it suitable for large-scale projects that require multi-utility layouts and future expansion capacity.

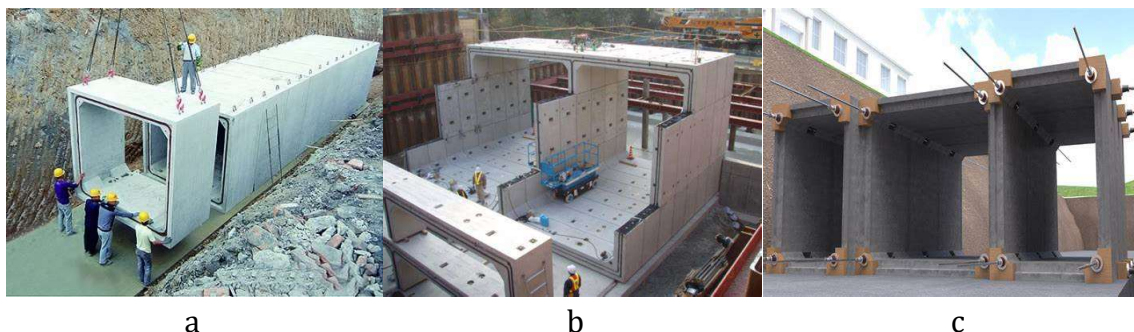


Figure 2. Typical cross-sectional forms of fully prefabricated concrete utility tunnels

In summary, fully prefabricated utility tunnels leverage factory-controlled production to replace on-site uncertainties, ensuring higher quality, shorter schedules, and lower environmental impact. This technology is increasingly becoming the mainstream solution in urban underground infrastructure development.

(2) Semi-Prefabricated Concrete Utility Tunnels

Semi-prefabricated concrete utility tunnels combine the advantages of factory prefabrication and on-site construction [12]. In this approach, major components such as pipelines, drainage channels, and cable troughs are prefabricated in controlled factory environments to ensure quality and precision, while other parts are cast on site. Prefabricated elements are transported to the construction site and integrated with in-situ works to form a complete tunnel system. This method enhances construction efficiency and quality while maintaining greater flexibility compared with fully prefabricated systems.

A key advantage of semi-prefabrication is that on-site casting of joints eliminates cross-sectional seams, thereby improving overall structural integrity and waterproofing performance. For this reason, semi-prefabricated tunnels are widely adopted in China. Two major forms are commonly used, as shown in Figure 3:

① Composite assembly type

The tunnel system is divided into multiple modules, each prefabricated in the factory and customized as needed. On site, these modules are stacked and assembled to create the complete structure. This approach provides design flexibility and modular adaptability, suitable for projects requiring diverse layouts and functions.

② Node cast-in-place assembly type

In this configuration, most tunnel structures are prefabricated, but critical joints-such as bends, intersections, and connections-are cast in place. This ensures enhanced integrity and stability at stress-concentrated locations. Compared with the composite assembly type, this method requires more on-site work but offers better reliability for complex geometries and high-stress areas.

In conclusion, semi-prefabricated concrete tunnels integrate factory precision with on-site adaptability, achieving a balance between efficiency, structural performance, and cost. They are particularly suitable for projects with moderate complexity and variable design requirements.



Figure 3. Construction methods of semi-prefabricated utility tunnels

(3) Steel Utility Tunnels

Steel corrugated pipe utility tunnels represent a novel form of prefabricated and assembled tunnel systems. They are typically composed of corrugated steel pipes, supporting frameworks, and connection components. The corrugated structure significantly enhances the load-bearing capacity and compressive strength of the pipes, while also providing flexibility to accommodate ground deformation and deflection. Supporting frameworks are used to stabilize and secure the pipes, and connection components link individual segments to form an integrated system.

This type of utility tunnel offers several advantages: ease of installation, long service life, and low maintenance costs. Due to the intrinsic properties of steel, these tunnels demonstrate strong compressive strength and corrosion resistance, making them suitable for a wide range of environmental conditions. In addition, their excellent sealing performance effectively prevents leakage of groundwater and wastewater, further enhancing durability. As a result, steel corrugated pipe utility tunnels have been increasingly applied in urban underground pipeline networks.

(4) Utility Tunnels with Novel Materials

In addition to conventional concrete and steel, new materials such as bamboo and polymer composites have been explored for utility tunnel construction.

Bamboo utility tunnels utilize bamboo as the primary material. Bamboo possesses natural growth advantages and favorable mechanical properties, including compressive strength, tensile resistance, and flexibility. Through proper processing and treatment, bamboo can be manufactured into pipelines, beams, and columns for tunnel components. This approach leverages bamboo's renewability and ecological benefits, offering potential for sustainable infrastructure applications.

Polymer-based utility tunnels generally adopt plastic pipelines as the main structural elements, supported and connected by auxiliary components. Commonly used polymers include polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). These materials are characterized by corrosion resistance, abrasion resistance, impact strength, and high sealing performance, making them suitable for various underground environments.

Based on the above analysis, the characteristics of different types of prefabricated assembly utility tunnels are summarized in Table 4.

Table 4. Comparison of the characteristics of various prefabricated integrated pipe corridors

Type of Utility Tunnel	Component Weight	Amount of Bracing & Formwork	On-site Workload	Structural Integrity	Waterproof Performance	Applicability
Integral segment prefabricated	Heavy	Low	Low	Good	Good	Suitable for small interfaces; single or double compartments
Block-segment prefabricated	Relatively light	Low	Low	Relatively good	Relatively good	Suitable for small- and medium-sized cross-sections
Multi-compartment prefabricated	Relatively heavy	Low	Low	Good (longitudinal), relatively good (transverse)	Good	Suitable for small compartments; allows multi-compartment and multi-level layouts
Composite assembly	Light	Relatively low	High	Good	Good	Suitable for multi-compartment and multi-level cross-sections
Node cast-in-place assembly	Light	High	Relatively high	Relatively good	Relatively good	Suitable for small- and medium-sized cross-sections
Steel corrugated tunnel	Light	–	Low	Good	Good	Suitable for small- and medium-sized single circular compartments
New-material tunnel	Light	–	Low	Good	Good	Suitable for small single circular compartments

3.2. Performance Design of Utility Tunnels

With continuous technological innovation, the performance of underground integrated utility tunnels has been significantly enhanced, particularly in seismic resistance and waterproofing. For seismic resilience, design strategies have been strengthened to ensure the stability and safety of tunnels during earthquakes. For example, Fasten Group has applied BIM technology to the design of integrated seismic supports for utility tunnels. The “BIM+” solution enables three-dimensional design, structural analysis, cost control, and intelligent prefabrication of seismic support systems before construction, ensuring both precision and efficiency.

In terms of waterproofing, advancements in sealing technologies have greatly reduced the risks of groundwater seepage and pipeline leakage, thereby ensuring long-term operational safety. Dayu Jiuding Co., Ltd. has continually improved its TPO self-adhesive pre-applied waterproof membranes, which are increasingly applied in underground utility tunnel projects. For instance, this product was successfully implemented in the Xiong'an New Area utility tunnel project, where subsequent feedback confirmed excellent performance and high user satisfaction [14].

In summary, innovations in seismic and waterproofing design provide reliable guarantees for durability, safety, and stability, thus laying a solid foundation for the sustainable development of urban underground infrastructure.

3.3. Application of BIM and GIS Technologies in Utility Tunnels

In recent years, the integration of Building Information Modeling (BIM) and Geographic Information System (GIS) technologies has been increasingly applied in the construction and management of underground integrated utility tunnels.

During the construction stage, BIM technology can be used to simulate the prefabricated assembly process of utility tunnels, as shown in Figure 4. In the operation and maintenance stage, BIM is employed to establish detailed three-dimensional digital models containing pipelines, equipment, and structural components, while GIS provides spatial information such as topography, geology, and surrounding underground pipelines. In addition, sensor networks can be deployed to monitor parameters such as temperature, humidity, pressure, and flow. By integrating real-time sensor data with BIM-GIS models, managers can achieve dynamic monitoring and data acquisition of tunnel operations.

Based on historical and real-time data, big data analytics and artificial intelligence algorithms (e.g., neural networks) can be applied to predict potential failures and generate early warnings. This predictive capacity enhances operational safety and reduces the risk of sudden failures. Furthermore, an integrated information platform can be established to enable data sharing and collaborative management across different departments, providing decision-makers with a visualized interface for real-time tunnel monitoring and management.



Figure 4. BIM-based construction simulation of prefabricated utility tunnels

4. Challenges in the Management of Urban Integrated Utility Tunnels

Urban integrated utility tunnels are critical components of modern infrastructure, enabling the consolidation of multiple underground pipelines and improving urban management efficiency and safety. However, significant challenges remain in their construction and management, including incomplete policies and regulations, high construction and operation costs, and complex system management.

4.1. Incomplete Policies and Regulations

China's rapid urbanization has driven large-scale infrastructure development, but utility tunnel planning only began to receive systematic attention in recent years. Due to the lack of historical planning experience and post-construction evaluation data, many plans have relied heavily on foreign models, which may not fully suit China's local conditions. This often results in limited practical applicability.

Inadequate analysis of local conditions—such as restrictions on underground space utilization, unique urban development needs, and existing pipeline complexity—further undermines planning feasibility. For example, insufficient consideration of limited underground space in central districts often leads to severe implementation difficulties, including the presence of underground obstacles and restricted construction sites.

Moreover, disconnection between planning and implementation is a common issue. While plans are developed under idealized assumptions, actual construction must contend with land use rights, demolition compensation, and technological limitations. These factors frequently necessitate substantial adjustments during execution, and in some cases, projects cannot be realized at all.

4.2. High Construction and Operation Costs

The extremely high costs of utility tunnel construction pose a heavy burden on local governments. Compared with traditional direct-buried pipelines, the construction cost of utility tunnels is significantly higher. For instance, in cities such as Shanghai and Hangzhou, the average cost of a main utility tunnel reaches 150–160 million RMB per kilometer, with some projects exceeding 200 million RMB. Civil works account for nearly ten times the cost of direct-buried pipelines.

In addition, operation and maintenance costs are also substantial. Utility tunnels require more inspection staff than direct-buried pipelines, along with complex auxiliary systems such as fire protection, lighting, monitoring, and ventilation. The energy costs, particularly electricity, can represent more than half of total operation expenses. However, most tunnel projects lack stable financial subsidies or diversified revenue streams, making it difficult for operators to achieve cost recovery. For utility companies, entry fees and additional operational expenses conflict with limited budgets, reducing their willingness to participate. Institutional restrictions in some state-owned enterprises further exacerbate this problem, preventing them from outsourcing maintenance and lowering overall operational efficiency.

4.3. System Complexity and Management Difficulties

Utility tunnels are highly complex systems that integrate not only multiple pipelines but also subsystems such as power supply, ventilation, monitoring, detection, and fire protection. Effective operation requires close coordination among these subsystems. The inclusion of high-risk utilities such as gas pipelines further raises design and construction requirements, necessitating explosion-proof facilities and leak detection systems, which increase technical difficulty and cost.

Furthermore, safety restrictions limit the co-location of pipelines. For example, gas pipelines cannot share compartments with electricity or telecommunications lines, and high-voltage

power cables must be separated from low-voltage and communication lines. This necessitates scientific compartmentalization and rational layout design to ensure safe operation.

Retrofitting existing pipeline networks for tunnel integration is another complex challenge. For instance, communication lines require relocation of optical distribution boxes and adjustment of data transmission systems to maintain service coverage, while sewer systems often need to be converted from traditional gravity flow to pressurized systems to function properly within tunnels. Such retrofits involve multiple technical disciplines and require careful planning to avoid disruptions to urban operations.

In summary, the major challenges of utility tunnel development in China are concentrated in three areas: delayed regulatory systems, unsustainable cost structures, and technical complexity of integrated management. Addressing these issues requires improvements in policy frameworks, financing mechanisms, and intelligent management approaches to ensure the sustainable development of utility tunnels.

5. Conclusion

This paper, through an in-depth analysis of the urban utility tunnel management model, proposes a series of optimization strategies and key technologies. These suggestions aim to enhance the construction efficiency, operational efficiency and sustainability of the utility tunnel. The research results are as follows:

5.1. Innovation in Management Models

(1) Promotion of the PPP Model

The Public-Private Partnership (PPP) model introduces private capital into infrastructure projects, effectively alleviating fiscal burdens on local governments while improving construction and operational efficiency. In utility tunnel construction, the PPP model offers distinct advantages:① Diversified financing-attracting private capital reduces reliance on public finance and allows government resources to be directed to other social needs;② Improved construction efficiency-private participation enhances design, construction, and project delivery, thereby shortening construction cycles;③ Advanced operational management-full life-cycle involvement of private stakeholders introduces modern management concepts and technologies, ensuring long-term effectiveness.

To ensure successful implementation of the PPP model, key measures include: scientific planning based on accurate demand forecasts, careful selection of PPP structures, transparent bidding to attract capable private investors, robust government supervision to prevent construction-operation imbalances, and dynamic performance evaluation mechanisms for continuous improvement.

(2) Corporatized Operation and Property-Based Management

Improving operational efficiency requires a shift to corporatized operation and professionalized property management. Dedicated utility tunnel operation companies should be established, adopting modern enterprise systems with clear governance structures, standardized procedures, and market-based mechanisms to improve competitiveness.

At the same time, drawing on property management practices, utility tunnels should be treated as specialized “properties,” with services such as inspection, repair, cleaning, and security provided to utility companies. Service standards and charging mechanisms should be clearly defined to ensure transparency and improve satisfaction among tenant utility providers.

(3) Establishment of a Paid-Use System

To ensure long-term sustainability, a sound paid-use system must be established. The guiding principles are:① Beneficiary pays-utility companies using the tunnels should bear corresponding costs [15];② Government-led, market-driven-government defines the

framework while market mechanisms govern resource allocation;③ Differentiated charging-fees vary by pipeline type, length, and spatial occupation, with reduced fees for critical lifeline utilities such as electricity and telecommunications;④ Transparency and accountability-charging standards and processes must be open to public oversight;⑤ Dynamic adjustment-charges should be revised in line with cost structures and market conditions.

Such a mechanism ensures stable funding sources for tunnel operation, improves cost recovery, and promotes both social and economic benefits.

5.2. Enhancement of Key Technologies

(1) Green Construction and Sustainable Materials

Green construction refers to the adoption of environmentally friendly practices during engineering projects, aiming to minimize resource consumption, reduce pollution, and achieve harmony with the surrounding environment. In utility tunnel construction, major measures include: optimizing construction schemes to reduce energy consumption; utilizing energy-efficient machinery and lighting equipment; establishing rainwater collection and wastewater treatment systems for water recycling; implementing waste classification and recycling programs; adopting effective noise reduction measures; and introducing soil protection technologies such as anti-seepage layers to prevent chemical contamination.

In terms of materials, priority should be given to low-carbon, recyclable, and environmentally sustainable options, including high-performance concrete, recycled aggregates, and green or ecological materials, to reduce lifecycle carbon emissions and enhance sustainability.

(2) Information Technology and Intelligent Monitoring Systems

The application of information technologies has become an essential driver for improving the efficiency and safety of utility tunnel construction and operation. BIM technology allows integrated modeling of design, construction, and management processes, improving design accuracy and reducing construction errors. Project management software enables real-time monitoring of progress, cost, and quality, while Internet of Things (IoT) applications support intelligent monitoring of construction equipment and environmental conditions.

In the operation stage, intelligent monitoring systems play a crucial role in ensuring safety and reliability. By deploying stress-strain, displacement, and tilt sensors, structural health conditions can be monitored in real time, with cloud-based data platforms providing early warnings of potential damage. Environmental monitoring systems, including temperature, humidity, and gas sensors, enable automatic adjustments to maintain stable tunnel conditions. Energy management systems integrate power distribution and lighting monitoring to reduce energy consumption and operational costs. Moreover, emergency response systems-consisting of alarm devices, sensor-triggered alerts, and coordinated evacuation protocols-ensure timely intervention in the event of fire, leakage, or other incidents.

5.3. Policy and Regulatory Recommendations

To ensure the smooth construction and operation of urban integrated utility tunnels and to promote standardized industry development, strong support at the policy and regulatory level is essential.

(1) Strengthening Top-Level Design and Improving the Policy Framework

It is necessary to accelerate the establishment of dedicated national legislation for integrated utility tunnels, clearly defining responsibilities and obligations across stakeholders and regulating construction, operation, and management processes. Complementary measures, such as fiscal subsidies, tax incentives, and financial support, should be introduced to encourage private sector participation, reduce investment risks, and improve project returns. For new urban roads and construction projects, mandatory pipeline inclusion in tunnels should be

stipulated, with a reasonable transition period to facilitate the gradual shift from aboveground to underground pipeline installation.

(2) Reinforcing Technical Standards and Guiding Industry Development

The technical standard system should be improved to cover the entire lifecycle of utility tunnels, including planning, design, construction, acceptance, and operation. Unified standards will enhance overall industry quality and safety. At the same time, regulatory bodies and responsibilities must be clarified, and a comprehensive supervision system should be established to ensure effective oversight throughout project implementation. Furthermore, the development of digital information management platforms should be promoted to enable pipeline data sharing, integrated management, and timely support for emergency responses.

(3) Enhancing Public Awareness and Fostering a Favorable Environment

Greater emphasis should be placed on public communication and industry outreach. Policy interpretation and the dissemination of technical standards should be strengthened to improve understanding and acceptance of utility tunnel projects. Successful experiences and best practices should be systematically summarized and promoted to provide references for other regions. In addition, universities and research institutes should be encouraged to establish related disciplines and training programs to cultivate technical and managerial talent, thereby ensuring a sustainable human resource base for industry development.

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