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Research on the Optimization of Municipal Water Supply and Drainage Design Based on the Sponge City Concept

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Abstract: The quality of water supply and drainage engineering directly affects urban operation and management levels. It is necessary to apply sponge city technologies to improve the water ecological resilience of cities, thereby achieving rapid absorption and allocation of water resources, meeting urban water requirements, and promoting efficient water resource allocation. This article takes the sponge city concept as the core, elaborates on its application significance in enhancing water resource utilization efficiency, strengthening urban disaster prevention and control resilience, and optimizing the ecological environment in municipal construction. It analyzes the core principles, typical strategies, and combination logic for selecting municipal drainage technologies. Finally, it explores the design optimization of municipal water supply and drainage in road systems, pipe networks, ancillary facilities, and ecological elements, aiming to provide reference opinions for relevant designers.

1. Introduction

With the continuous acceleration of urban construction in China and the increasing abundance of advanced technologies employed, urban construction, as an important foundation for ensuring residents' lives, faces the growing urban population. The public has put forward higher requirements for the operational quality and efficiency of water supply and drainage systems. Against this backdrop, it is necessary to strengthen the application of the sponge city concept in the field of water supply and drainage and deeply integrate it into the planning and construction of municipal water supply and drainage facilities. By doing so, the collection efficiency of rainwater resources and drainage effects can be improved, the water storage and drainage functions of the water supply and drainage system can be further enhanced, and ultimately, the optimal allocation of urban water resources can be achieved.

2. Application Significance of the Sponge City Concept

In practical applications, the value of the sponge city concept in municipal construction is mainly reflected in the following three aspects. Firstly, it promotes a systematic improvement in water resource utilization efficiency. After optimizing the functions of the municipal water supply and drainage system based on the actual needs of the city, rainwater can be transformed from a "drainage burden" into an "available resource." By storing rainwater, it can meet the demands for non-potable water such as greening irrigation and sanitation cleaning, thereby reducing dependence on municipal water supply and alleviating the contradiction between urban water supply and demand, forming a circular chain of water extraction, utilization, storage, and reuse [1]. Secondly, it strengthens the resilience of urban disaster prevention and control. This concept can reduce the peak operating pressure of the water supply and drainage system through flexible facility design, avoiding sewage overflow caused by pipeline network overload during extreme rainfall events. At the same time, by promoting rainwater infiltration and detention, it reduces surface runoff and lowers the probability of urban waterlogging from the source, enabling the city to shift from "passive flood fighting" to "active storage and regulation." Thirdly, it assists in the restoration and optimization of the urban ecological environment. The deep integration of the sponge city concept with environmental protection concepts can reduce the obstruction of soil infiltration caused by

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hard paving, promote groundwater recharge, and also reduce the impact of pollutants carried by rainwater runoff on natural water bodies, improving the local micro-ecology of the city. This helps alleviate the ecological damage caused by traditional water supply and drainage systems and enhances the overall livability of the city.

3. Selection of Municipal Drainage Technologies Based on the Sponge City Concept

3.1 Core Principles for Technology Selection

Technology selection should take site adaptability as the primary prerequisite and then make comprehensive decisions in combination with factors such as soil permeability, underground space distribution, and topographical characteristics [2]. In areas with insufficient soil permeability, permeable paving or bioswales should be prioritized to avoid over-reliance on infiltration-based technologies. For sites with underground spaces, permeable paving should be overlaid with a covering layer and a drainage layer with a thickness of no less than 0.6 m to prevent infiltration risks. In areas with a longitudinal slope exceeding 4%, bioswales should adopt a stepped design and be equipped with energy dissipation devices to control water flow velocity. Meanwhile, technology selection should also be guided by functional requirements for differentiated selection. If the core objectives are peak shaving and groundwater recharge, permeable paving is the preferred option. Motorways can use permeable asphalt concrete, while non-motorways can use permeable bricks and stones. Additionally, a maintenance plan to prevent clogging should be planned simultaneously. If there is a need to balance water purification and ecological restoration, bioretention technology is more suitable. In highly polluted areas, pre-treatment methods such as grassed swales with sedimentation should be strengthened, and water-resistant vegetation and highly permeable soils should be selected. In areas where rainwater reuse requirements are clear, underground storage tanks should be prioritized for construction. These facilities not only have a low pollution risk but can also be connected to the existing drainage system. However, they should be avoided in heavily polluted areas. For areas with a catchment area of no less than 1 hm^2, infiltration ponds offer higher cost-effectiveness. When constructing them, pre-facilities such as sand sedimentation tanks should be provided. In winter snowmelt areas, anti-salt damage measures should also be added. Furthermore, it is necessary to focus on controlling environmental risks to avoid the limitations of technologies. In high-altitude areas, the cost of soil replacement should be evaluated first for bioretention technology. If the cost is too high, a combination of bioswales and storage tanks should be used as an alternative. Infiltration ponds should maintain a safe distance from residential areas. When there is water body pollution nearby, anti-seepage design should be strengthened. Before constructing storage tanks, water quality should be tested first. In areas where pollution exceeds standards, transfer-type facilities such as transfer bioswales should be used instead.

3.2 Selection Strategies for Typical Technologies

Firstly, permeable paving is suitable for hard-paved areas such as urban roads and squares. The key points for selection are reflected in two aspects. When the road surface strength is insufficient, a semi-permeable structure should be adopted to balance the bearing capacity and permeability functions. At the same time, it can be combined with non-permeable paving, using a point-line-plane combination method to optimize the durability of facilities in high-frequency use areas. Secondly, bioretention technology is suitable for residential green spaces and road green belts. The key points for selection need to focus on soil infiltration rate and drainage time control. When the soil infiltration rate is lower than 12.5 mm/h, a drainage layer should be added to convert it into a partially infiltrating type. In addition, referring to the T/CUWA 40052-2022 specification, the designed drainage time should be controlled within 12–24 h, and it can be extended to 48 h in areas with less human activity [3]. Thirdly, infiltration ponds are suitable for large parks and ecological corridors. The key points for selection are to control pond parameters and system connections. The distance between the pond bottom and the groundwater level should be no less than 1 m, and the slope of the side slope should not exceed 1:3. The overflow water level should be more than 0.6 m above the pond bottom. Additionally, they can be connected in series with bioswales to form a system, replacing traditional pipelines to improve transmission efficiency. Finally, the selection of storage tanks and bioswales needs to be clearly classified. For large-scale construction, storage tanks should preferably be made of reinforced concrete, while for small-scale construction projects, brick and stone materials can be used [4]. Moreover, storage tanks should adopt a closed design to prevent mosquito breeding. When bioswales assist storage tanks, dry or wet types can be selected. When used solely for transfer, transfer-type bioswales should be chosen, and the cross-section should preferably adopt an inverted parabolic or inverted trapezoidal shape.

3.3 Application Logic for Technology Combination

A single technology can no longer cover the full-process needs of infiltration, transfer, purification, and reuse in sponge cities. Therefore, a collaborative system needs to be established [5]. Firstly, the drainage system in road areas can be built through a combination of permeable paving, bioswales, and sand sedimentation tanks. This combination can form a closed loop of infiltration, transfer, and purification, thereby improving the drainage efficiency in road areas. Secondly, the drainage and reuse system in residential areas can be established by combining bioretention facilities, underground storage tanks, and bioswales. Rainwater is collected through bioswales, purified through bioretention facilities, and stored in storage tanks to meet the needs of landscape irrigation and reuse. Thirdly, the ecological drainage system in large green spaces can be constructed by combining infiltration ponds, pre-ponds, and ecological buffer zones. This combination can strengthen peak shaving effects and groundwater recharge functions, meeting the ecological drainage needs of large green spaces.

4. Optimization of Municipal Water Supply and Drainage Design Based on the Sponge City Concept

4.1 Optimization of Drainage Design in Municipal Road Systems

Firstly, roadbed design needs to be deeply coordinated with pipeline planning. Designers should introduce Building Information Modeling (BIM) technology at the design stage to model and analyze the layout of roads and underground water supply and drainage pipelines, and optimize the planning scheme in real-time to avoid drainage blockages caused by pipeline conflicts. Meanwhile, for roadbeds with poor permeability, the construction team should take improvement measures such as rolling, sun-drying, and backfilling to enhance the roadbed's permeability and reduce surface water accumulation at the source. In addition, designers should clarify the layout requirements for water supply and drainage pipelines in accordance with current standards to simultaneously improve road surface engineering design, ensuring that the roadbed and pipelines can work together for drainage [6]. Secondly, road surface design needs to be optimized differentially according to usage scenarios. In the design of sidewalks, designers should prioritize the use of cost-effective, breathable, and highly permeable new materials and plan drainage paths in combination with the city's topographical characteristics to ensure rapid infiltration of road surface rainwater. In the design of vehicle lanes, designers should balance traffic safety and drainage efficiency. On the one hand, they can increase the density of drainage systems and improve the flatness of road surface structures to meet the needs of high-speed vehicle travel. On the other hand, they should focus on improving drainage performance and select high-quality new materials to reduce the retention time of rainwater on the road surface. Finally, green belt design needs to integrate water storage, filtration, and reuse functions. Designers should reasonably set the elevation of green belts and the layout of rainwater collection points, control the height of collection inlets between green belts and sidewalks, and equip them with filters to prevent blockages by debris, ensuring smooth rainwater collection. On this basis, in the structural design of green belts, designers should lay planting soil at the bottom, cover it with gravel on the upper layer, and embed permeable pipes to establish a simple rainwater filtration system for preliminary purification of rainwater. Moreover, designers should design drainage ditches and overflow systems. The former can assist in water storage to alleviate drainage pressure during the rainy season, while the latter can be connected to the water supply and drainage system to further improve the operational efficiency of the drainage project. The stored rainwater can also be used for greening irrigation, thereby improving water resource utilization efficiency.

4.2 Optimization of Water Supply and Drainage Pipe Network Design

Firstly, pipe network design needs to strengthen pre-survey and differentiated zoning. At the pipe network design stage, designers should conduct pre-surveys to clarify the locations and depths of existing drainage pipe networks in urban areas, avoiding damage to existing facilities caused by new pipe network construction. Meanwhile, for the water supply system, designers should differentiate municipal water supply pipe networks from fire water supply pipe networks according to functional differences. The water supply pressure of municipal water supply pipe networks is usually controlled within 0.3–0.4 MPa, while the pressure of fire water supply pipe networks needs to be higher than this standard. Designers should avoid pressure confusion that may lead to damage to the water supply system or pipeline leakage, and also reasonably utilize the residual pressure of the water supply system to improve energy utilization efficiency. Secondly, pipe network parameter and layout design should take into account both practicality and maintainability. When laying pipelines, designers should plan along straight lines, set pipeline corners at positions convenient for maintenance, and construct inspection wells simultaneously to reduce problems such as interface leakage and blockages. In addition, during the design process, designers should combine comprehensive geophysical prospecting technology and BIM technology to optimize the spacing between drainage pipelines and existing pipelines, ensuring a reasonable layout [7]. Moreover, designers should accurately calculate and determine pipe diameters and pipe wall thicknesses according to local meteorological and rainfall characteristics, as well as pipeline water supply pressure and transmission distance, to ensure that the pipe network can adapt to drainage needs under different working conditions. Finally, pipe material selection should follow the principle of adaptability. Designers should compare the performance of various pipe materials such as concrete and cast iron and select pipe materials with better weather resistance and anti-leakage properties in combination with factors such as pipe network pressure requirements and transmission environment to reduce pipe network damage and water pollution problems caused by inappropriate pipe materials and improve the long-term drainage stability of the pipe network.

4.3 Optimization of Integrated Design of Ancillary Facilities and Ecological Elements

On the one hand, the design of ancillary facilities needs to promote integrated optimization. At the preliminary design stage of ancillary facilities, designers should conduct a comprehensive survey of the current situation of urban water supply and drainage engineering to clarify whether various design indicators meet regulatory requirements. On this basis, they should improve the functional layout of ancillary facilities. Meanwhile, designers should optimize the selection of building materials and construction schemes to enhance the durability and drainage adaptability of ancillary facilities. For example, integrating rainwater diversion and sunken greening measures can strengthen the facilities' ability to and retain rainwater. In addition, designers should pay attention to the connection between greening nodes and ancillary facilities, introducing new technologies and concepts to improve drainage performance, ensuring that ancillary facilities and the main drainage system complement each other and improve overall drainage efficiency.

On the other hand, plant selection should highlight ecological adaptability to assist in strengthening drainage and rainwater purification effects. Designers should prioritize plants with deep and well-developed root systems to fix the soil through their roots and prevent soil erosion caused by rainwater scouring. The selected plants should have strong rainwater purification and filtration capabilities to adapt to scenarios such as rain gardens and sunken green spaces, which serve as "temporary rainwater storage reservoirs." They should also have both flood-tolerant and drought-tolerant characteristics to ensure survival and functional performance under different precipitation conditions [8]. In addition, designers should combine regional climate, transportation costs, and post-maintenance requirements to prioritize the use of local plants to reduce maintenance difficulty. Then, through a reasonable combination of multiple species, they can improve the city's landscape effect while meeting drainage and purification needs, achieving a win-win situation between ecological benefits and drainage functions.

5. Conclusion

The sponge city concept provides a systematic innovative approach for the field of municipal drainage, with the core being to break the traditional rigid drainage mode and achieve coordinated symbiosis between cities and natural hydrology. From technology selection based on site adaptability, functional requirements, and risk prevention and control to design optimization targeting road systems, water supply and drainage pipe networks, and ancillary ecological elements, the focus has always been on the coordinated efforts of "infiltration, storage, utilization, and drainage," transforming rainwater from a "burden" into a resource while strengthening urban waterlogging prevention and control and ecological restoration capabilities.

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