Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.30011

313 (2023) 227–235
November

Vertical spatial optimization design of drainage water treatment facilities in coastal cities under storm surge environment

Ming Yan[a], Yonggang Cheng[b], Miao Wu[c,]*

[a]*School of Construction Engineering and Design, Wuhan Institute of Shipbuilding Technology, Wuhan 430050, China*
[b]*School of Water Resources and Hydropower Engineering, Wuhan University, Wuhan 430072, China*
[c]*School of Faculty of Environmental Design, Wuhan Institute of Design and Sciences, Wuhan 430200, China, email: wumiao1807@163.com*

Received 2 June 2023; Accepted 12 August 2023

ABSTRACT

Coastal cities, as the key areas for the transition of land and sea, tend to be more affected and damaged when facing the marine natural disasters dominated by storm surges. In view of this, under the guidance of the design concept, this study defines and screens the key elements of vertical space in coastal cities from the macro, meso and micro levels. Meanwhile, the optimization index items of key elements of vertical space under various scales are set, and the vertical space system of coastal cities is constructed from the perspective of storm surge disaster prevention, which makes the work content and objects of vertical space design optimization clearer. Through practical application, detailed optimization strategies and methods are proposed for the vertical space system of coastal cities, aiming at providing more optimization possibilities for the vertical space of coastal cities, improving the regional storm surge prevention and disaster adaptation ability, and maintaining the healthy and sustainable development of the region. The simulation results show that the maximum road water depth caused by rainfall in 10 and 50 y is reduced by 2.31 cm after the spatial optimization strategy is adopted. The maximum depth of road waterlogged water decreased by 3.35 cm due to rainfall during the 100-y recurrence period. This scheme has good application value.

Keywords: Storm surge; Coastal cities; Drain water; Vertical space

1. Introduction

In urban planning, vertical space plays an important role in urban drainage, flood control and waterlogging. Vertical space determines the coordination degree of urban surface water environment. As the product of highly developed cities, whether the vertical space design of coastal cities is reasonable or not is directly related to whether the region can develop sustainably and healthily in a complex environment [1]. At present, the vertical space design of coastal cities is based on the norms and standards of general land cities, and continues the consistent idea of vertical site design and coastal dike design [2]. However, compared with inland cities, coastal cities also have their own characteristics and characteristics. Coastal cities are located at the frontier of land and sea interface and are vulnerable to strong storm surge [3]. In addition, there may be land reclamation areas in coastal cities, and the land use intensity in these areas will be much higher than that in general land areas due to high construction costs. Therefore, this area is prone to urban waterlogging due to high degree of surface hardening and poor permeability [4]. Due to its special geographical location, the region is more exposed to the sea and more vulnerable to the impact of sea tide rise and fall. At present,

---

* Corresponding author.

although the vertical spatial planning of coastal cities can ensure that the project meets the cost, safety and ecological requirements, it is easy to ignore the environmental characteristics of coastal cities, resulting in poor disaster prevention and reduction [5]. Coastal dike-based disaster prevention cannot completely eliminate the impact of storm surge disaster, and it may even lead to worse conditions due to dike-breaking. Therefore, this study defines and screens the key elements of vertical space of coastal cities from macro, meso and micro levels, respectively, and constructs the vertical space system of coastal cities from the perspective of storm surge disaster prevention, so as to make the vertical space planning of coastal cities more accurate and clearer.

2. Related work

Storm surge disaster is a common marine disaster. The sudden change of marine environment conditions leads to the occurrence of storm surge disasters, which will also cause malignant events that harm society, economy, environment and life and property in coastal areas. At present, the study of storm surge mainly involves the characteristics analysis of storm surge disaster, disaster simulation, risk assessment and prevention. Many researchers have launched a heated discussion on this issue. In order to understand the occurrence rhythm of storm surge disasters in detail, Wang et al. [6] collected statistical data of storm surge in the past 20 y for analysis. The scope, distribution and temporal and spatial characteristics of storm surge were detected and discussed by visual method. Finally, the empirical results summarized the disaster characteristics of storm surge and laid a foundation for formulating disaster prevention and reduction strategies. Wang et al. [7] collected detailed data of 2,018 storm surge disasters in the history of China to analyze their frequency and spatial and temporal distribution. This study summarized the spatio-temporal characteristics of extreme storm surge disasters from the aspects of contributing factors, damage records, mitigation measures and tropical cyclone tracks. This study provides great help for disaster managers to formulate corresponding measures to prevent and control storm surges. From the perspective of storm surge disaster prevention coordination in coastal cities, Huang et al. [8] constructed an evaluation model of disaster prevention and reduction cooperation degree of coastal cities based on capacity coupling coefficient. The model uses the principal component analysis method to test the feasibility and effectiveness of the index system. The evaluation results effectively prove that the proposed method can provide targeted suggestions and policy basis for the disaster prevention and reduction system of coastal cities. In order to make timely development of disaster prevention and mitigation measures for coastal cities, Yu et al. [9] chose to assess the vulnerability of storm surge. This study combined the single assessment method and the weighted combination method to calculate the social vulnerability index. The empirical analysis takes Shenzhen City, China as an example, and calculates the historical data of its storm surge. This study can provide reference value for coastal cities to make post-disaster emergency plans. Starting with the storm surge disaster risk assessment, Wang et al. [10] constructed a set of storm surge disaster assessment methods based on numerical simulation system. The system combines the inundation area and depth with the disaster bearing agency data to evaluate the storm surge risk. The test results of Wenchang City in Hainan Province show that the proposed method can obtain the risk distribution level map of this region, which provides scientific support for coastal zone governance and marine disaster prevention and reduction.

Urban spatial optimization design involves many research fields, such as urban waterlogging prevention, underground space planning, etc., which has been discussed by many scholars. In order to solve the problem of unreasonable spatial layout of urban block traffic network, Wang et al. [11] analyzed the spatial characteristics of historical blocks and established a game model of road space optimization. The effectiveness of the proposed model is verified by an example. This study has instructive significance for vertical space optimization of urban drainage facilities. Sun and Leng [12] found that rational use of underground space can save land, relieve traffic pressure and improve resource utilization, so they proposed an underground space optimization method to improve people's travel quality and efficiency. Taking an underground space in Nanjing City as an example, this paper quantifies the travel factors of underground space by field measurement, POI, space syntax and other multi-source methods. This study has positive reference significance for other cities in China to develop underground space. From the perspective of improving the quality of public space in coastal cities, researcher Zhu [13] constructed a structural optimization design method of public space in coastal cities based on interaction design. This method analyzes the macro and micro elements of public space in coastal cities and puts forward some optimization ideas. The advantages of the proposed method have been verified in detail by the final simulation experimental data. Wang et al. [14] studied the underground space planning of coastal cities and built a three-dimensional geological model of the whole sedimentary layer based on geotechnical investigation. The data set is used to estimate the number of existing underground structures, and the underground space resources are evaluated on this basis. The spatial conceptual planning in this model can be applied to other spatial optimization projects and has high reference value.

To sum up, storm surges do more harm to coastal cities. In addition, so far, there are only a few studies on vertical spatial optimization of drainage facilities in coastal cities. Therefore, this study screened the key elements of vertical space of coastal cities and constructed the vertical space system of coastal cities from the perspective of storm surge disaster prevention, so as to improve the rationality of vertical space planning of coastal cities.

3. Construction of vertical spatial system of drainage facilities in coastal cities under storm surge environment

3.1. Key factors of vertical space of coastal cities at various scales

The vertical space system mainly includes two parts: key elements and optimization index. The key elements of vertical space refer to all kinds of spatial entities and are design elements in different scales. Optimization index item refers to the control points of various key factors, namely the index affecting the effectiveness of key factors [15]. The key elements and optimization indexes together constitute the vertical space system, and clearly and fully indicate the connotation of vertical space design. At the macro scale, the vertical space of coastal cities shows the most important three-dimensional structure of the region mainly through the transition between the relative height difference and different datum planes, and then completely reflects the overall relationship of the region in vertical. This vertical overall relationship is the basis for coastal cities to cope with storm surge disasters, and is also the key to meet the needs of disaster prediction [5]. Under this scale, the key elements of vertical space can be abstracted into three parts: low datum level space, high datum level space and boundary space, as shown in Fig. 1.

On the mesoscale, the vertical space of coastal cities shapes a series of spatial systems with specific functions through a certain hierarchical structure. These spatial systems can provide useful spatial places for absorbing and channelling storm surge disasters, emergency evacuation, and avoiding disasters [16]. The establishment of a series of vertical space systems is an important step for coastal cities to make up for their own crisis management of storm surge disasters. According to the disaster-response function, the key elements of vertical space in coastal cities can be divided into four parts: vertical system of disaster bearing and disaster-removing, vertical system of emergency traffic and vertical system of avoidance and safety at the mesoscale, as shown in Fig. 2.

On the micro scale, the vertical space of coastal cities can be transformed into a single building, structure or facility. Through the design of form, structure and combination relationship, vertical space can form specific functions to meet the needs of spatial disaster prevention [17]. From the perspective of disaster prevention function, the key elements of vertical space of coastal cities on a micro scale can be divided into four categories: waterlogging regulation and storage space, drainage and dredging space, traffic channel and shelter space, as shown in Fig. 3.

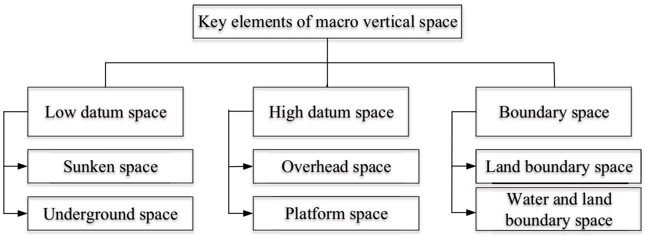


Fig. 1. Key elements of macro vertical space.

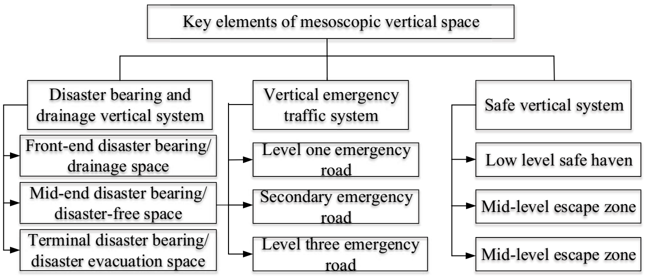


Fig. 2. Key elements in vertical space.

3.2. Optimization index of key factors in vertical space of coastal cities

After analyzing and summarizing the key factors of vertical space in coastal cities, it is necessary to determine the optimization index of key factors. In order to optimize the key elements of vertical space, a reasonable operation index must be found. Analytic hierarchy process (AHP) index screening method will be adopted to screen the key factors optimization index items in vertical space of coastal cities. If the number of criteria is too large, multiple sub-criteria layers should be decomposed. Firstly, a preliminary index system was established, and then the scale of judgment matrix elements was set, as shown in Table 1.

Then the judgment matrix is constructed. Judgment matrix refers to the comparative results of all factors at a certain level against the relative importance of a factor at the next level. The judgment matrix compares the factors in pairs rather than together. Therefore, the number of comparison factors in the judgment matrix should not be too much, because too much judgment matrix will affect its accuracy. For example, compare all the elements of layer C in pairs with those of the previous layer B, Bj. The judgment matrix is shown in Table 2.

After that, a consistency check is performed. The eigenvector corresponding to the maximum eigenvalue is used as the weight vector of the influence degree of the compared factor on the upper factor. The greater the degree of inconsistency, the greater the judgment error. Inconsistency is measured by λ–n. Consistency test calculation formula is shown in Eq. (1).

$$\text{CI} = \frac{\left(\lambda_{\max} - n\right)}{\left(n-1\right)} \tag{1}$$

where $\lambda_{\max}$ is the largest characteristic root of the matrix, and the calculation formula is shown in Eq. (2).

$$\lambda_i = \sum_{j=1}^{n} \frac{a_{ij} w_j}{w_i} \tag{2}$$

Consistency ratio CR is the ratio of CI to RI. RI is the average random consistency index, and the arithmetic

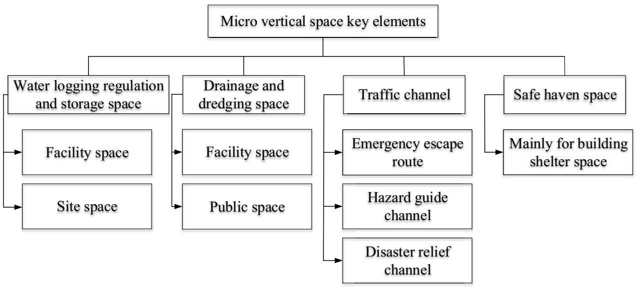


Fig. 3. Key elements in micro vertical space.

Table 1
Scale assignment table of analytic hierarchy process analysis method

Scale	Meaning
1	Means that both factors *i* and *j* are equally important
2	Comparing the two factors, *i* is slightly more important than *j*
3	Comparing the two factors, *i* is significantly more important than *j*
4	Comparing the two factors, *i* is more important than *j*
5	Comparing the two factors, *i* is more important than *j*
1/2	*i* is slightly less important than *j*
1/3	Comparing the two factors, *i* is significantly less important than *j*
1/4	It doesn't matter if *i* is stronger than *j*
1/5	Comparing the two factors, *i* is less important than *j*

Table 2
Analytic hierarchy process analysis matrix list

C1	C11	C12	C1i	C1n
C2	C21	C22	C2i	C2n
……	……	……	……	……
Ci	Ci1	Ci2……	Cii……	Cin
……	……	……	……	……
Cn	Cn1	Cn2……	Cni	Cnn

Table 3
RI value table of analytic hierarchy process analysis method

Order	RI
3	0.58
4	0.9
5	1.12
6	1.24

mean value is obtained after repeated eigenvalues of the random judgment matrix, as shown in Eq. (3).

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \tag{3}$$

The RI values of each order are shown in Table 3.

When CR < 0.1, the matrix consistency is the best. Otherwise, the assignment adjustment calculation of the judgment matrix should be carried out again until it meets the above conditions. Finally, the weight is calculated and the judgment matrix C eigenvector $\text{CW} = \lambda_{\max}\text{W}$ is calculated. Wherein, $\lambda_{\max}$ is the largest characteristic root of C; W is the corresponding normalized feature vector; The component of W represents the weight of the corresponding indication as shown in Table 4.

Select the index trade-off weight (x) and screen the index. According to Saaty, the founder of AHP, most people's ability to distinguish between different things on the same attribute is between 5 and 9. Therefore, the number of indicators under a certain criterion should not exceed 9. More indicators can reduce the weight, which is 0.05 in this study. When the index is small, the weight can be increased, and 0.15 is adopted in this study. According to relevant data and basic research, related indicators of vertical space design are preliminarily sorted out, and the optimization index system of key elements of vertical space of coastal cities is obtained, as shown in Fig. 4.

Table 4
Calculation method of analytic hierarchy process analysis method

Evaluation index	Multiply	Square root	Weight
C1	$c11\times c12\times c1i\times\ldots\times c1n$	$\overline{W}1 = \sqrt[n]{c11\times c12\times\ldots c1n}$	$W1 = \frac{\overline{W1}}{\text{WP}}$
C2	$c21\times c22\times c2i\times\ldots\times c2n$	$\overline{W}2 = \sqrt[n]{c21\times c22\times\ldots c2n}$	$W2 = \frac{\overline{W2}}{\text{WP}}$
……	……	……	……
Cn	$cn1\times cn2\times cni\times\ldots\times cnn$	$\overline{W}n = \sqrt[n]{cn1\times cn2\times\ldots cnn}$	$Wn = \frac{\overline{Wn}}{\text{WP}}$
Total		$\text{WP} = \sum_{i-1}^{n}\overline{Wi}$	$\sum_{i-1}^{n} Wi = 1$

4. Validation of vertical space optimization of drainage facilities in coastal cities under storm surge environment

4.1. Calculation of vertical space optimization system of drainage facilities based on AHP

Since macro indicators (B1), meso indicators (B2) and micro indicators (B3) are equally important, they are not compared with each other, and only the weight calculation of indicators at the project level is considered. Since the optimization of key elements of vertical space belongs to space design and planning, and there are few macro and meso index items, an expert in the field of urban design is invited to carry out the scoring process. Micro index design specific facility design, so invited an expert in the field of municipal engineering design to give a score. According to the collation of the counter score table and calculation of subordinate macro index (B1), meso index (B2) and micro index (B3), the judgment matrix can be obtained according to the values given by experts, as shown in Table 5.

According to the above ideas, under the guidance of the concept of non-structural disaster reduction and the concept of multidimensional scale correspondence, with the design goal as the important guidance and the vertical space system as the starting point, specific optimization indicators for the vertical space of drainage facilities in coastal cities are proposed to verify. In this study, the influence factors of AHP analysis are combined with internal and external factors for evaluation analysis, so as to achieve the purpose of accurate positioning. This research method is helpful to make scientific and effective decision in vertical space optimization of drainage facilities. At the same time, the expert survey method is applied to construct the hierarchical structure model, and the total weight and consistency test results of each factor decision analysis are obtained, as shown in Table 6.

There are three indexes under the dependent macro index (B1), and the maximum characteristic root is 3.0183. Consistency test CR 0.02, less than 0.1, meet the requirements of consistency; By calculating the weight value, the weight of C11, C12 and C13 is 0.5585, 0.1218 and 0.3196, respectively. The weight of index C12 is less than 0.15, which is a weak weight index, so it is deleted in the final index system. There are three indexes under the dependent meso index (B2), and the maximum characteristic root is

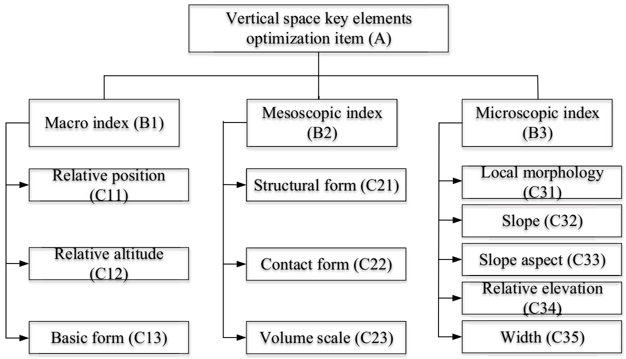


Fig. 4. Optimization index system of key elements in vertical space.

Table 5
Indexes of subordinate macro indexes (B1), meso indexes (B2) and micro indexes (B3)

B1	C11	C12		C13	
	1	4		2	
A=	1/4	1		1/3	
	1/2	3		1	
B2	C21	C22		C23	
	1	1/2		3	
A=	2	1		5	
	1/3	1/5		1	
B3	C31	C32	C33	C34	C35
	1	2	3	4	5
	1/2	1	2	3	4
A=	1/3	1/2	1	4	5
	1/4	1/3	1/4	1	5
	1/5	1/4	1/5	1/5	1

Table 6
Weight and consistency test of internal and external factors

First-order index	First-order index weight	Secondary index	C R	Secondary index weight	Total weight
		C11		0.5585	0.1836
B1	0.298	C12	0.02	0.1218	0.0400
		C13		0.3196	0.1050
		C21		0.309	0.1016
B2	0.191	C22	0.003	0.5816	0.1912
		C23		0.1094	0.0360
		C31		0.4143	0.1362
		C32		0.2675	0.0879
B3	0.511	C33	0.09	0.2108	0.0693
		C34		0.1073	0.0353
		C35		0.0454	0.0149

3.0037. Consistency test CR is 0.003, less than 0.1, meeting the requirements of consistency; By calculating the weight value, the weights of C21, C22 and C23 are 0.3090, 0.5816 and 0.1094, respectively. The weight of index C23 is less than 0.15, which is a weak weight index, so it is deleted in the final index system. There are five indexes under the dependent microscopic index (B3), and the maximum characteristic root is 5.4029. Consistency test CR is 0.09, less than 0.1, meeting the requirements of consistency; By calculating the weight value, the weights of C31, C32, C33, C34 and C35 are 0.4143, 0.2675, 0.2108, 0.1073 and 0.0454, respectively. The weight of index C35 is less than 0.05, which is a weak weight index, so it is deleted in the final index system.

This study also analyzes the design decisions of internal and external key factors, as shown in Table 7. The weighted weight is the product of weight and score, and the sum of the weighted values of internal and external key factors can be obtained as 0.648 and 1.654, respectively.

Create a coordinate system with origin (0,0) and coordinates (0.648,1.654) in the first quadrant. In this quadrant, the factors of external and internal advantages are well matched. The vertical space design location of coastal urban drainage facilities under storm surge environment is shown in Fig. 5.

Table 7
Group decision analysis results of internal and external key factors

			Weight	Score	Weighted value
External key factor	B1	C11	0.062	5	0.306
		C12	0.03	5	0.146
		C13	0.108	4	0.429
	B2	C21	0.018	–3	–0.052
		C22	0.052	–3	–0.154
		C23	0.014	–2	–0.027
	Total	\	\	\	0.648
Internal key factor	B3	C31	0.16	3	0.478
		C32	0.268	5	1.336
		C33	0.077	4	0.305
		C34	0.133	–2	–0.265
		C35	0.056	–3	–0.166
	Total	\	\	\	1.654

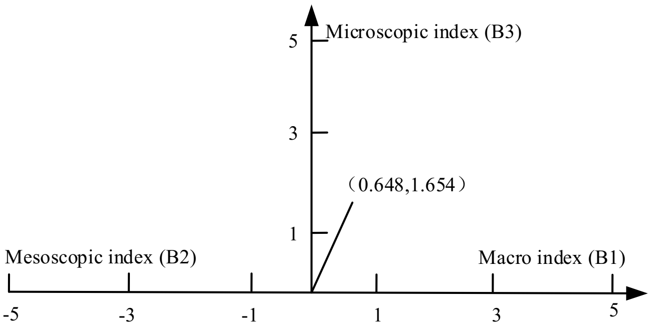


Fig. 5. Vertical spatial design location of drainage facilities in coastal cities under storm surge environment.

Under the disaster prediction goal, after considering the disaster control, stability and equilibrium of the space, coastal cities should not choose the macro form with high seaside and low land side, but should choose the macro form with high and low side. Under the gradient adaptation objective, the vertical system of disaster bearing and drainage should be changed from series structure to progressive structure. The form of internal connection changes from dendritic to unidirectional coupling between multiple levels. The vertical system of emergency traffic should adopt series-connected structure, two-way coupling between multiple levels, and take into account the continuity of normal traffic. The safety vertical system should adopt progressive series compound structure; The only two-way link between the high-level and mid-level safe havens; The bidirectional coupling between the middle level and the low level of the risk zone provides a diversified risk space. Under the goal of facility efficiency, open water inlet should be set up in the space of waterlogging regulation and storage facilities, which is directly connected with the external environment, and gradient overflow should be set up in the drainage outlet. The space of waterlogging regulation and storage site should be set up in combination with subsidence square and subsidence green space, and the underground drainage system with large depth should be considered. The public space mainly considers the relative relationship of each important elevation of landscape watercourse to ensure water exchange and drainage needs.

4.2. Case analysis

This study takes the vertical design of drainage facilities in a coastal city as an example to optimize the vertical design of drainage and dredging space in the city. At the same time, the drainage and dredging space is set as the facility space represented by side ditch, culvert and drainage pipe network. The vertical optimization of facility space is mainly achieved by improving the drainage capacity of side gully, which can be achieved by increasing the velocity or the section area. Water velocity is related to engineering materials, technology and roughness, and the improvement is small only through shape design. On the other hand, for urban drainage pipe network, on the basis of ensuring drainage slope and buried depth, pipe diameters at all levels should be appropriately expanded to improve the adaptability to high-intensity drainage. For side gullies and culverts on the surface, the elevation of the bottom surface can be further lowered, and the section shape can be adjusted to improve the drainage and dredging ability [18]. For drainage channels with larger flow and higher levels, the design can be considered combined with non-motorized traffic space, so as to provide additional capacity for drainage and dredging space with disaster levelling state transition as shown in Fig. 6.

The non-motorized lanes or sidewalks on both sides of the road are sunk. Road side ditch is located on the outermost side of the whole road, unilateral catchment, in normal state will not interfere with the traffic use of the road. But when a storm surge disaster occurs, the tide that exceeds the drainage capacity of the side gully can be contained by the sinking space of non-motorized lanes or sidewalks. In other words, non-motorized traffic changes from general

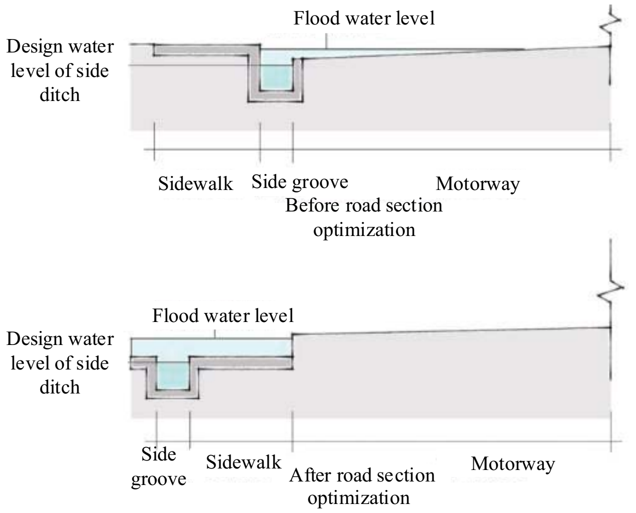


Fig. 6. Optimization diagram of the combination of side ditch and traffic space.

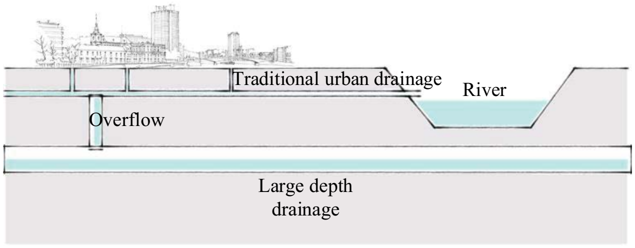


Fig. 7. Schematic diagram of large depth underground drainage system.

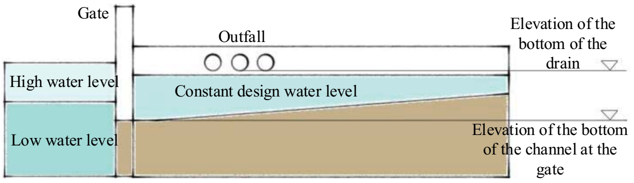


Fig. 8. Design of main elevation points of landscape watercourse.

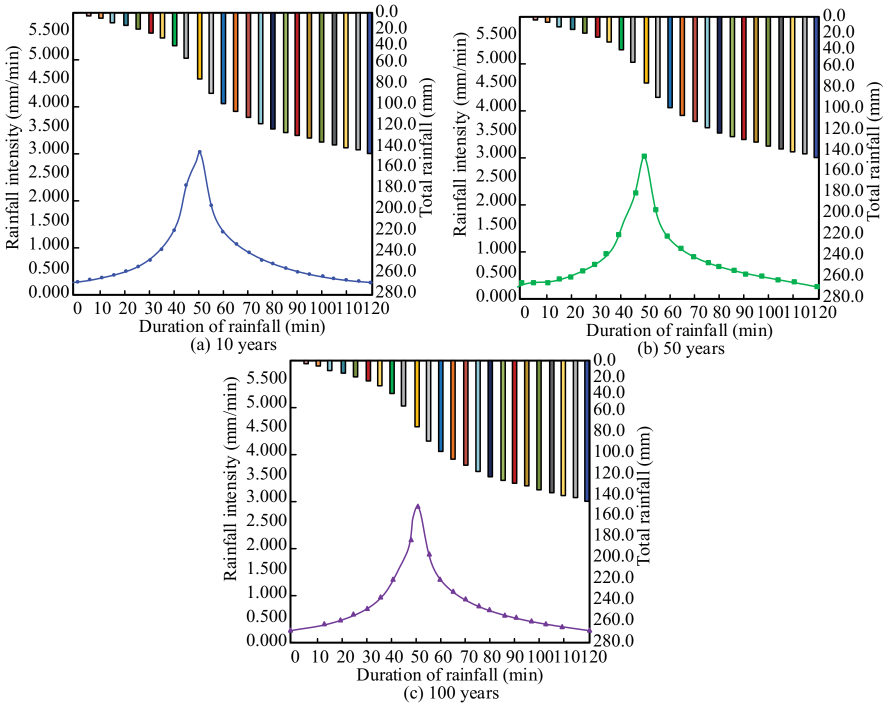
traffic space to drainage space through the change of disaster state, providing extra capacity for roadside ditch. This conversion takes full advantage of the close relationship between the drainage arrangement and the urban road, and also maximizes the use of space. In addition, in the reclamation area, the construction of urban underground drainage system with large depth can also greatly improve the storm surge prevention capacity. According to the Special Practical Measures Law on Large Depth Underground Public Space promulgated by Japan in 2000, the definition of large depth underground space mainly refers to the space below the depth that landowners are usually unable to utilize [19,20]. Large depth underground drainage system has been widely applied in developed foreign cities, such as Tokyo, Paris, Chicago, Munich, etc. The basic form is shown in Fig. 7.

According to the design in Fig. 7, the overloaded part of the urban shallow drainage system or the inland river can be collected through overflow to relieve the pressure of urban surface and shallow drainage. In addition, the invasion tide brought by storm surge disaster can also be well regulated and stored. However, the current system also has problems such as imperfect regulations, difficult construction and long period [21]. If the relevant problems can be coordinated or dealt with well, it can be applied as the main compensation for the vertical space of reclamation area in disaster prevention level.

Landscape river channel is an important public space of drainage and dredging in reclaimed land area, which has certain disaster absorbing capacity. Considering the demand of drainage and dredging and the demand of regular water exchange in landscape river course, the design water level of regular time should be lower than the high tide of surrounding seawater and higher than the low tide of surrounding seawater. In addition, the elevation of the bottom surface of the channel at the gate should be the lowest point of the whole channel bottom, as shown in Fig. 8. The design in Fig. 8 not only ensures that the landscape river channel can be opened at low tide to withdraw water, but also at high tide to replenish water, so that the water body exchange is sufficient, but also ensures that the river channel can smoothly return to the normal design water level after the storm surge disaster.

To better verify the effectiveness of the proposed strategy, this study took a coastal city as an example to simulate the urban road rain and flood damage scenarios before and after the spatial optimization of the urban drainage system. The cause of the flood disaster is the comprehensive influence of precipitation and production and accumulation of two environmental factors. Based on different rainfall models, this study sets the research object as the road in the south of the study area, and establishes the scenario simulation of rain and flood damage before and after spatial optimization of drainage system. The rainfall process curve is generated by the Chicago rain generator, and its specific rainfall function distribution is shown in Fig. 9.

Fig. 10c and e, respectively show the spatial and temporal distribution of water accumulation under the scenario that rainfall return period is 10, 50 and 100 y before spatial optimization of drainage system. Fig. 10b, d and f, respectively show the spatial and temporal distribution of water accumulation under the scenario that the rainfall return period is 10, 50 and 100 y after spatial optimization of drainage system. It is not difficult to find from the figure that, before the spatial optimization of road drainage system, the maximum water depth occurred in the 72–93 min of the road section during the rainfall recurrence period of 10, 50 and 100 y, which were 11.23, 13.45 and 15.26 cm, respectively. After road reconstruction, the spatio-temporal distribution of the three parameters after spatial optimization of the drainage system basically did not change, and the values were 9.26, 11.34 and 11.89 cm, respectively. The results show that the longer the precipitation repetition time, the more rainfall, the greater the water depth. After the spatial optimization of the drainage system, the maximum road water depth caused by the rainfall in the 10 and 50-y recurrence periods decreased by 2.31 cm, and that caused by the rainfall in the 100-y recurrence period decreased by 3.35 cm. Therefore, the effectiveness of the strategy is verified [22].

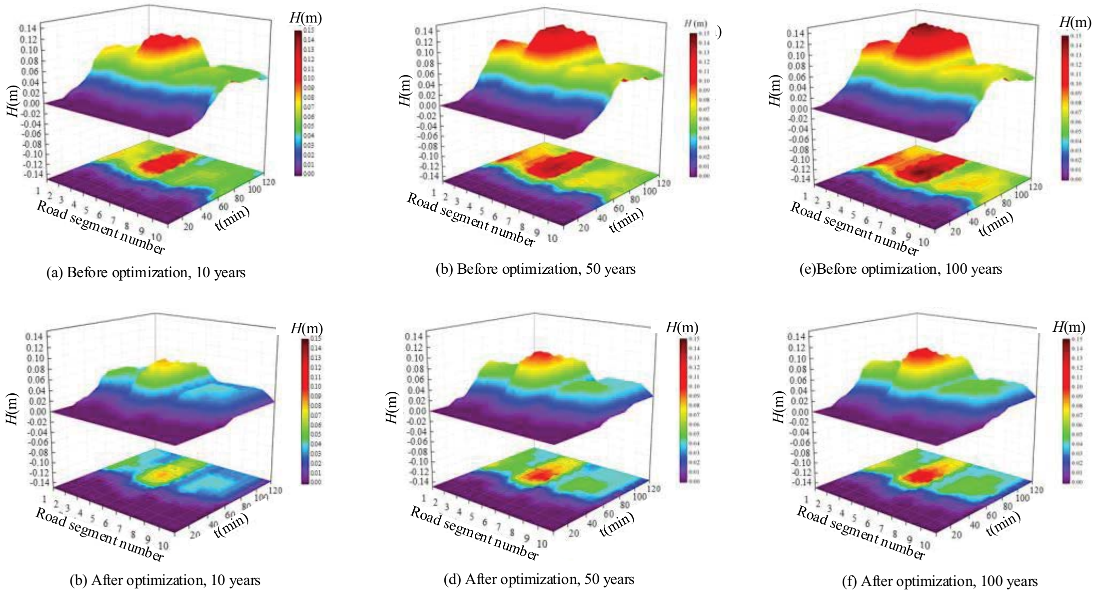


(a) 10 years

(b) 50 years

(c) 100 years

Fig. 9. Distribution of rainfall function.



(a) Before optimization, 10 years

(b) Before optimization, 50 years

(e)Before optimization, 100 years

(b) After optimization, 10 years

(d) After optimization, 50 years

(f) After optimization, 100 years

Fig. 10. Road water distribution before and after spatial optimization of drainage system.

5. Conclusion

This study uses the method of case analysis to optimize the vertical space of coastal urban drainage facilities based on storm surge environment. The design defines and screens the key elements of vertical space in coastal cities from macro, meso and micro levels. At the same time, the optimization index items of key elements of vertical space under various scales are set, and the vertical space system of coastal cities is constructed from the perspective of storm surge disaster prevention, which makes the work content and objects of vertical space design optimization clearer. Under the guidance of disaster prediction objective, gradient adaptation objective and facility efficiency objective, vertical spatial optimization of coastal cities at macro, meso and micro levels was carried out, respectively. The simulation analysis of the proposed strategy was carried out in a coastal city. The results showed that, before the spatial optimization of drainage system, the rainfall recurrence period was 10, 50 and 100 y, and the maximum water depth was 11.23, 13.45 and 15.26 cm, respectively. After spatial optimization of the drainage system, the values of the three parameters are 9.26, 11.34 and 11.89 cm, respectively. After the spatial optimization of the drainage system, the maximum water depth of the road decreased by 2.31 cm due to the rainfall in the 10 and 50-y recurrence periods. The maximum depth of road waterlogged water decreased by 3.35 cm due to rainfall during the 100-y recurrence period. This verifies the effectiveness of the research space optimization strategy. In this study, there are few discussions on the influence of the utilization of intelligent electronic components inside buildings in coastal cities, and more attention will be paid to this discussion in future studies.

References

[1] X. Shi, Z. Han, J. Fang, J. Tan, Z. Guo, Z. Sun, Assessment and zonation of storm surge hazards in the coastal areas of China, Nat. Hazards, 100 (2020) 39–48.

[2] Y. Ide, M. Yamashiro, N. Hashimoto, Proposal of new indexes for development characteristics of storm surge considering topographical features and tides, Coastal Eng. J., 63 (2021) 107–125.

[3] K.Y. Lim, K.Y. Foo, A State-of-the-Art Review on the Unique Characteristics, Key Driving Causes and Mitigation Measures of the World Catastrophic Flood Disasters, C. Ghosh, S. Kolathayar, Eds., A System Engineering Approach to Disaster Resilience, Lecture Notes in Civil Engineering, Vol. 205, Springer, Singapore, 2022. https://doi.org/10.1007/978-981-16-7397-9_17

[4] Z. Fang, Y. Wu, H. Zhong, J. Liang, X. Song, Revealing the impact of storm surge on taxi operations: evidence from taxi and typhoon trajectory data, Environ. Plann. B: Urban Anal. City Sci., 48 (2021) 1463–1477.

[5] K.D.C.R. Dissanayaka, N. Tanaka, T.L.C. Vinodh, Integration of Eco-DRR and hybrid defense system on mitigation of natural disasters (Tsunami and Coastal Flooding): a review, Nat. Hazards, 110 (2022) 1–28.

[6] Y. Wang, J. Liu, X. Du, Q. Liu, X. Liu, Temporal-spatial characteristics of storm surges and rough seas in coastal areas of Mainland China from 2000 to 2019, Nat. Hazards, 107 (2021) 1273–1285.

[7] K. Wang, Y. Yang, G. Reniers, Q. Huang, A study into the spatiotemporal distribution of typhoon storm surge disasters in China, Nat. Hazards, 108 (2021) 1237–1256.

[8] X. Huang, J. Song, X. Li, H. Bai, Evaluation model of synergy degree for disaster prevention and reduction in coastal cities, Nat. Hazards, 100 (2020) 933–953.

[9] H. Yu, Y. Shen, R.M. Kelly, X. Qi, K. Wu, S. Li, H. Yu, X. Bao, Trends in social vulnerability to storm surges in Shenzhen, China, Nat. Hazards Earth Syst. Sci., 20 (2020) 2447–2462.

[10] Y. Wang, Z. Guo, S. Zheng, M. Zhang, X. Shu, J. Luo, L. Qiu, T. Gao, Risk assessment for typhoon-induced storm surges in Wenchang, Hainan Island of China, Geomatics Nat. Hazards Risk, 12 (2021) 880–899.

[11] Q. Wang, Y. Yan, K. Wang, Research on optimized design of road space in mixed sections of historical district: a case study of Xi'an, China, Can. J. Civ. Eng., 48 (2021) 1105–1114.

[12] L. Sun, J. Leng, Research on influencing factors of travel in underground space based on multi-source data: spatial optimization design for low-carbon travel, Energy Build., 253 (2021) 111524, doi: 10.1016/j.enbuild.2021.111524.

[13] X. Zhu, Optimization design of public space structure in coastal cities based on interactive design, J. Coastal Res., 104 (2020) 751–755.

[14] J. Wang, Y. Su, H. Wang, Y. Shi, D. Chen, Q. Gu, X. Liu, Evaluation of urban underground space resources in a delta coastal city, IOP Conf. Ser.: Earth Environ. Sci., 861 (2021) 052068, doi: 10.1088/1755-1315/861/5/052068.

[15] A. Singh, A.K. Sarma, J. Hack, Cost-effective optimization of nature-based solutions for reducing urban floods considering limited space availability, Environ. Processes, 7 (2020) 297–319.

[16] J. Gao, J. Li, Y. Li, J. Xia, O. Lv, A distribution optimization method of typical LID facilities for sponge city construction, Ecohydrol. Hydrobiol., 21 (2021) 13–22.

[17] S. Mohammadiun, J. Yazdi, J. Hager, S.A.A. Salehi Neyshabouri, R. Sadiq, K. Hewage, A. Alavi Gharahbagh, Effects of bottleneck blockage on the resilience of an urban stormwater drainage system, Hydrol. Sci. J., 65 (2020) 281–295.

[18] V.P. Sethi, M. Dhiman, Design, space optimization and modelling of solar-cum-biomass hybrid greenhouse crop dryer using flue gas heat transfer pipe network, Sol. Energy, 206 (2020) 120–135.

[19] A. Jooya, N. Dimopoulos, A. Baniasadi, Multiobjective GPU design space exploration optimization, Microprocess. Microsyst., 69 (2019) 198–210.

[20] H.-L. Wu, W.-C. Cheng, S.-L. Shen, M.-Y. Lin, A. Arulrajah, Variation of hydro-environment during past four decades with underground sponge city planning to control flash floods in Wuhan, China: an overview, Underground Space, 5 (2020) 184–198.

[21] C. Pei, X. He, L. Cao, J. Zhu, M. Liao, H. Guo, Geological Problems and Economic Evaluation for Underground Space Utilization, Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 174 (2021) 63–75.

[22] M. Shahin, M. Billah, Md. Mozahidul Islam, A. Parvez, A.K.M.M. Zaman, Cyclone shelters need sustainable development, Int. J. Disaster Resilience Built Environ., 11 (2020) 659–678.