Research on Storm Surge Adaptive Landscape Infrastructure

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ABSTRACT

This paper outlines the rising sea level and the growing threat of storm surge, and analyzes the types and shortcomings of existing defense facilities. It also proposes that the landscape acts as an infrastructure to adapt to the storm surge, and compares the various landscape infrastructure and analyzes its advantages, disadvantages and applicability. Finally, the paper summarizes the superiority of landscape infrastructure compared with traditional grey infrastructure, and then proposes the prospects for its development.

INTRODUCTION

From 1901 to 2010, the global average sea level rise reached 0.19 meters. From the mid-19th century, sea level rise was much larger than that in the past 2000 years. In the next few hundred years or even thousands of years, the global average temperature will rise by 1-4 degrees Celsius, causing sea level rise of 4-6 meters [1]. This will cause areas with lower altitudes to be inundated and coastal cities will face enormous threats. The increased water salinity by seawater intrusion will cause great damage to the ecosystem and seriously threaten the ecological balance of the marine and coastal freshwater environment. In addition, rising sea levels make storm surges more frequent and cause more severe damage. Now, the world's 46 million people are affected by the storm surge. If the sea level continues to rise by 50 centimeters, the number of people affected will increase to 92 million. If it rises by 100 centimeters, the affected population will reach 118 million [2]. It can be seen that under the background of global climate change and rising sea level, storm surge disasters are becoming more and more serious. How to do a good job of storm surge

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prevention will be an important issue that determines the survival and development of coastal cities.

EXISTING GREY INFRASTRUCTURE AND SHORTCOMINGS

The expansion of cities, land reclamation and other activities have made people face the storm surge more directly, and the ground subsidence, narrowing of river channels, and hardened ground have also caused the storm surge to become more and more serious. Nowadays, people's engineering and technical level is unprecedentedly developed, and they have gained more initiative in storm surge defense. The hard engineering facilities (also called grey infrastructures) with obvious effects have become the main way to resist the storm surge. It is mainly divided into four categories: 1) fortifications that are parallel to the coast and located on the coast, such as seawalls, pavements, and revetments; 2) parallel to the coast and outside the coast, such as breakwaters, longitudinal dams; 3) perpendicular to the coast and located on the coast, such as spur dikes, training dikes; 4) floodgates. Although these grey infrastructures have obvious defense effects in the short term, they also have the following problems:

Impact on The Ecosystem

These fortifications will have an impact on coastal sediment deposition, marine migration, seawater salinity, seawater circulation and water quality. For example, the California Waterway Project in the United States reduced the amount of freshwater resources flowing into the San Francisco Bay by 40%, affecting the habitat of aquatic organisms, and also causing seawater inversion and soil salinization. Similarly, China's Three Gorges Project has also intensified seawater intrusion into the Yangtze River estuary. The annual seawater intrusion is more serious when the water level in the river is reduced. This trend will be further aggravated with the completion of the South-North Water Transfer Project [3]

High Construction and Maintenance Investment

The storm surge defense project is often a large-scale project in the region, so it takes a lot of manpower and material resources in the design and construction process. In South Africa, seawalls can usually only work for a year and destroyed by continuous waves [4]. The construction of floodgates is a large project that requires huge financial resources. For example, the flood control scheme in New York will cost 20 to 25 billion US dollars to build, and the huge maintenance and management costs will make it difficult to implement. At the same time, with the increasing storm surge under climate change, its requirements for defense engineering facilities are getting higher and higher in order to guarantee the safety of the city.
Single Function Defense Mode

The goal of modern engineering facilities from the beginning of design and construction is to defend against storm surges, and rarely consider adding other functions. So the result is that these facilities only play a defensive role for defensive purposes. In addition, most engineering facilities are serviceable in the event of a storm surge, which is a small probability event. In normal times, there is often no obvious practical use, resulting in a waste of resources.

Lack of Macro-efficiency Coordination

The spur dike and groin will interfere with normal sediment flow and destroy the natural sediment balance. Although the construction of the groins can intercept more sediment deposits and prevent coastal erosion, the excessive sediment interception in the upstream can lead to insufficient sediment in the downstream, resulting in greater coastal erosion downstream (see Figure 1). Similar to flood gates, it will also cause greater flooding in the surrounding areas. Therefore, modern storm surge defense facilities are local protection strategies often at the expense of other regional interests.

![Figure 1. Groins’ influence towards sedimentation.](image)

Splitting The City Texture

Engineering facilities, such as seawalls, cut the original continuous coastal space into land and sea, making it difficult for people to get close to the waterfront. And the waterfront is the most dynamic part of the city. Now, it easily synonymous with
danger and fear because of disaster prevention. The floodgates require a large area to be built. In addition to the gate itself, the remaining space will not be easily utilized and become a corner of the city's leftover space, which is lack of vitality.

**STORM SURGE ADAPTIVE LANDSCAPE INFRASTRUCTURE**

Landscape infrastructure is a new concept relative to grey infrastructure. It was first proposed by Garry Strang in 1996 [5]. Based on previous research, Pierre Blang proposed a comprehensive concept of “landscape infrastructure” that extends the scope of landscape infrastructure to “systematic, service-oriented, larger-scale, a landscape that carries resources and energy flows that reflects the urban development process and dynamic changes; and is an important carrier for supporting and nurturing urban economic development [6]. In terms of storm surge adaptation, there are mainly the following ways:

**Landscape Infrastructure Unit**

**DOUBLE DUNE SYSTEM**

Sand dunes are naturally formed protective belts on many beaches. On the basis of natural sand dunes, people developed a double dune system(see Figure 2), that is, the first layer is a sacrificial dune and the second layer is a protective dune. When the storm surge hits, the first layer of sand dunes played a major role in resisting, which caused a large amount of sand loss, but absorbed most of the energy of the waves, which greatly reduced the impact of the waves. Under the protection of the first layer of sand dunes, the second layer of sand dunes further absorbs the energy of the waves, with less sand loss, and finally blocks the storm surge outside them, thus protecting the surrounding communities. At the same time, in order to enhance the defense effect of sand dunes, it is possible to combine the vegetation planting, fix the sand dunes through the cultivation of beach grass and other shrub trees. Sand dunes can not only play a role in storm surge defense, but also have a high tourist appreciation value. In the storm surge adaptive landscape infrastructure construction, this feature can be combined to form a unique coastal landscape. Sand dunes are suitable for construction in places with existing source of sand and convenient transportation, because sand dunes need to be replenished from time to time, and it is not suitable in places where coastal erosion is serious.
CONSTRUCTED WETLAND

Although there is still no in-depth quantitative research on the defense effect of wetlands on storm surges, a large number of cases in reality show that wetlands do have the effect of weakening the impact of storm surges. At the same time, the wetland also has a variety of ecological functions, including water purification, providing ecological environment for animals and plants, stagnant silt, and preventing coastal erosion. It can also provide social service functions such as bird watching, fishing, and recreation. Because of its limited ability to withstand storm surges, wetlands are suitable for sites where the impact of the waves is less severe, but if combined with other engineering facilities such as seawalls, they can also adapt to strong impact protection. Also, wetlands are suitable for construction in river deltas and sedimentary deltas, and require a gentle slope. The construction of constructed wetlands requires a leveling of the site and appropriate filling to create a suitable depth of water. The construction cost of wetlands is much smaller than the traditional grey infrastructure. And in addition to the usual small maintenance, the wetland does not need to be repaired manually after the storm surge (see Figure 3).
RETENTION PONDS

Retention ponds mainly refer to waters enclosed by dikes or dunes, mounds, etc., which can retain the tidal water and increase the roughness to reduce the impact of storm surges (see Figure 4). Facilities like detention pools have always been used in China and the West. For example, the coated land invented in the coastal areas of ancient China is to build a dam to retain seawater, which can be used for sea salt production and to play a certain role in flood control. The Netherlands has similar creations and is called Polder. Polder uses earth dams to enclose water bodies to promote sediment deposition for agriculture. Recently, Polder proposed a strategy of accepting periodic flooding, which played a role in flood discharge and mitigation of flood shocks. By combining with other landscape means, the detention pool can also be used as a farmland, a breeding ground, boating area, sightseeing and other activity space. Retention ponds generally require a larger site to implement, and it is better to link pieces into a whole. Therefore, it is more suitable for open lowlands. For densely populated and highly developed sites, it is not suitable because of the high cost of migration. In addition, because of its large footprint, the impact on the ecological environment is still unclear.

Figure 4. Retention pond.

ARTIFICIAL REEFS

Artificial reef is an aman-made island constructed of stone, concrete, or other materials, it is used to weaken the impact of waves while providing habitat for marine life (see Figure 5). Artificial reefs are often used to improve coastal habitats. Recently it has been studied as an “offshore ecological breakwater” to mitigate storm surges. Its porous and coarse interface can effectively absorb the impact of the waves, and the plants and animals that grow on it can also play the role of stagnation and anti-wave. Artificial reefs can be constructed from a variety of materials, including stone, silt, rubber, glass, shells and shaped concrete, as well as other recycled materials. After the reef island is stabilized, marine animals and plants
(such as oysters, clams, barnacles, etc.) begin to occupy each pore, making it an “ecological breakwater”. The artificial reefs have strong resistance to storm surges and is suitable for a wide area, but it is most suitable in shallow waters. Artificial reefs can protrude from the surface of the water or sink into the water, so the visual impact on the environment is small. In addition, due to the diversity of materials, it has increased flexibility and can be selected according to budget and environmental conditions. At the same time, artificial reefs can reshape diverse ecosystems by providing habitats and provide services such as recreation and education.

Figure 5. Artificial reefs.

FLOATING ISLANDS

The floating island is a floating structure with vegetation covering, which can reduce the impact of waves and provide habitats for animals and plants and purify water quality (see Figure 6). Ocean dynamics studies have found that the impact of waves occurs mainly in the upper layers of seawater. In this principle, a floating breakwater was invented, and the floating island, which has more ecological function through the vegetation, is based on the floating breakwater. A buoyant material fixed to the sea floor generally supports the floating island, and a porous material is mounted thereon as a fixture for the plant, and the plant roots are allowed to grow in the seawater through the fixture. Because of its unfixed nature, floating islands are not suitable for setting in large waves. Due to its simple structure, the floating island is easy to install and the cost is relatively low. However, the application of floating islands is still in the untested stage, and the tolerance of the storm surge and its impact on the environment are still unclear.
RIPRAP

Although the riprap bank is made up of gravel, a common material used in traditional grey infrastructure, it is considered a high-quality landscape infrastructure due to its outstanding defensive capabilities and ecological characteristics (see Figure 7). First of all, compared with the traditional vertical bank, the riprap bank can allow the seawater to pass through, so that the direct impact force is small, and the multi-layered gravel absorbs the impact force in a geometrical order. Therefore, the riprap shore is not easy to destroy and is more stable. Secondly, the gap between the riprap can provide a place for the habitat of animals and plants, forming a small ecosystem that is in harmony with nature. Animals and plants not only can slow down the impact of the waves, but also promote sediment deposition and make the riprap shore more stable. The riprap bank is suitable for construction on a site that already has a hard revetment and requires a relatively stable foundation, and is not suitable for construction on the natural coast, because it will cause damage to the intertidal zone. Because of its good hydrophilicity, the riprap bank is also suitable for construction in waterfront parks and docks, and the cost is low.
| Unit               | Function                                     | Advantage                                                                 | Resistance | Applicability | Costs          | Others                                      |
|-------------------|----------------------------------------------|---------------------------------------------------------------------------|------------|---------------|----------------|------------------------------------------------|
| Double dune system| Wave attenuation of the waves; slow down coastal erosion; promote flood discharge. | Form a coastal landscape; Little impact on the environment; can digest dredged sediment. | Strong     | Existing low-lying beaches; convenient transportation; not suitable for areas with severe coastal erosion. | $150,000/acre | Sediment may need to be contaminated. |
| Constructed wetland | Weeken the impact of the waves; slow down coastal erosion; promote flood discharge. | Create intertidal habitats; purify water; provide fishing, bird watching and other recreational activities; intercept floating debris in storm surges. | Weak       | Protected water bay and river estuary delta; slower slopes; suitable for areas with large waves. | $700,000/acre | Impact resistance needs to be studied; it will affect the construction of other engineering measures. |
| Retention ponds    | Weeken the impact of the waves; slow down coastal erosion; promote flood discharge. | Available for recreation in the usual time. | Relatively strong | In the protected water bay and the waterfront park. | Unknown. | Lack of in-depth research if it may have an impact on coastal ecosystems. |
| Artificial reefs    | Weeken the impact of the waves; slow down coastal erosion; promote flood discharge. | Small visual impact; diverse materials, wide adaptability; creating habitats; providing social functions such as recreation and education. | Relatively strong | Most effective in shallow waters, also suitable for areas with large waves. | Differs with the material. | Lack of in-depth research if it may have an impact on coastal seawater dynamics. |
| Floating islands   | Weeken the impact of the waves; slow down coastal erosion; promote flood discharge. | Low cost, easy to install; create habitats, purify water bodies. | Weak       | Protected water bays and areas where the waves are not strong. | $80/ft. | Lack of in-depth research if the shadows it creates may have an impact on marine life. |
| Riprap             | Stabilize shoreline, slow down coastal erosion; promote flood discharge. | Low cost, low maintenance; little impact on surrounding sediment deposition; water shore accessibility. | Relatively strong | There is already a hard revetment site; relatively stable foundation; it is not suitable for construction on the natural coast. | $2,000-$5,000/ft. | Slope and stone size need to be studied separately according to the site. |

The costs is cited from *NYC Urban Waterfront Adaptive Strategies*. 
Landscape Infrastructure Combined With Grey Infrastructure

The modern grey infrastructure, such as seawall, revetment, breakwater, dike, floodgate, have certain shortcomings, such as damage to the ecological environment, high construction and maintenance costs, and separation of urban texture. But it is undeniable that these grey infrastructures also have their advantages and their irresistibility in storm surge defense. First, the grey infrastructures have better defense cap ability against high-intensity storm surges. Many landscape infrastructures, such as wetlands, floating islands, and retention ponds, appear to be less effective faced with strong ocean waves. For example, the 1m high wetland in New Orleans in the United States can slow down the storm surge of 30cm height, but when the storm surge is higher than 6m, the wetland can play a very limited role [7]. Secondly, based on thousands of years of storm surge defense history, the city's coastline is basically occupied by grey infrastructure. If it is completely converted into landscape infrastructure, it will consume a lot of manpower and economic resources, and it will have a major impact on urban layout. Again, there are certain inherent flaws in the landscape infrastructure. Some animal and plant materials with good storm surge protection effect such as Spartina alterniflora are likely to cause species invasion, destroy local ecosystems, and threaten local ecological balance. In addition, due to the serious pollution caused by the coastal areas in the city, many areas are not suitable for the growth of animals and plants.

Therefore, the storm surge adaptive landscape infrastructure is actually the organic integration of the two. For the grey infrastructure that has been built and is not easy to reconstruct, it is mainly through the transformation of landscape means to increase its ecological and social functions. For projects that are not built, the integration and collaboration of the two needs to be taken into account during the design and planning phase. For example, for the reconstruction of the seawall, it can be combined with landscaping facilities such as riprap shores and wetlands to increase its ability to defend against storm surges, while enriching the habitat and providing habitat for animals and plants. Above the seawall, it is also possible to combine the roads, observation decks, etc. to increase the social, transportation and recreation functions (see Figure 8).

Figure 8. Landscape infrastructure combined with grey infrastructure.
CONCLUSIONS

Compared to the traditional grey infrastructure, the landscape infrastructure is first of all different in concept, from “defense” to “adaptation”. “Adaptation” affirms that the storm surge is a product of nature, and human beings (also as a part of nature) should learn to coexist with it and even use it. The landscape infrastructure has a better natural connection, which can make up the gap between the city and nature. At the same time, the landscape infrastructure also emphasizes that the attitude toward the storm surge is not a hard resistance, but through coordination to achieve the dynamic balance between the two. It also reflects the flexibility and adjustability of the landscape infrastructure, because the landscape infrastructure itself is the carrier of animals and plants, so it has stronger dynamic properties. In addition, the landscape infrastructure is a stronger functional complex, which not only provides the functions of absorbing carbon dioxide to release oxygen, purifying air, water, soil and water, etc., but also meeting the needs of urban traffic, drainage, sewage, ventilation, temperature regulation. It can also improve environmental comfort and meet social requirements such as aesthetics, public welfare, education, and recreation. The diversity of functions also contributes to the formation of an organic composite system, thereby improving the overall flexibility. Therefore, in terms of storm surge adaptability research, the landscape infrastructure has great potential and need to be continually studied, and it is also suitable to be combined with the existing grey infrastructure, so that people can better cope with sea level rise and storm surge disaster.

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