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A Methodological S

tudy on the Design of low-carbon and environmentally-friendly baffles Based on Mangrove Bionics

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Abstract: The current disaster prevention and mitigation engineering design fail to balance aesthetic ornamental and low-carbon environmental method. In this study, bionic design method was adopted to solve this problem based on mangroves properties. Wave protection properties of mangroves are proposed to design debris-disaster prevention baffles applicable to natural scenic areas. The research methodology is: (1) A six elements and ten steps design method, the critical bionic elements of mangrove plants were extracted, which aimed to retain the original wind and wave protection performance. (2) based on the Analytic Hierarchy Process method (AHP), a decision objective model was constructed. Furthermore, the critical bionic design elements were prioritized and selected to build a geometric structure model. (3) Compared the disaster mitigation performance through numerical studies, the best design elements were seleted for further studies. (4) based on the above theoretical guidance, low-carbon concept, and environmentally-friendly principles, the final disaster prevention baffle was designed. This studies show that using bionic design method satisfies aesthetic ornamental and low-carbon environmental protection. The use of AHP avoids subjective one-sidedness in design process when considering the priority of bionic elements. The numerical simulation experiments adopted in this study aimed to compare the blocking effect of different baffle models. The optimization of traditional baffles groups conducted in this studies., Finally, the disaster prevention will be improved. In this study, the bionic product design methodology is adopted for baffle design to solve existing aesthetic and environmental problems. The particle accumulation mass after the new baffles can be effectively reduced by 2~3 times when compared with the traditional baffles. Furthermore, the new baffle is more aesthetically pleasing than that of traditional baffles.

Keywords: Mangroves; Bionics; Disaster prevention and mitigation; Product design; Discrete element method

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Introduction

1.1. Mangroves and their ecological effects

Mangrove is a tidal wetland woody biome that grows on mudflats in the border zone between land and sea, a unique ecosystem in the transition from the teerestrial kingdom to the acquatic one. Mangroves consist of evergreen shrubs or trees dominated by mangrove plants, composed of herbaceous and vine mangroves with respiratory or strut roots [1]. Figures 1(a) and 1(b) are mangrove plants and habitats, respectively. Mangroves have a high ecological value, with functions such as wind and wave protection, siltation and beach protection, shore protection, and seawater purification [2]. In 1986,

the 398 km long seawall in Hepu County was swept across 294 km by waves during a significant storm surge off the coast of Guangxi, China, but where mangroves were present outside the dike, the dike was not easily swept across [3]. The 2004 Indian Ocean tsunami struck 12 countries and regions, killing 230,000 people. In contrast, 172 families in the fishing village of Sernarthorpe, India, just a few dozen meters from the coast, were lucky to escape the tsunami because of a dense mangrove forest growing on the beach [4], Figure 1(c) shows 2004 Indian Ocean tsunami. In 2012 the Cambridge University Coastal Research Group found[5] that wave heights decrease when waves pass through mangroves. In a mangrove of 500m in width, wave heights would be reduced by between 50% and 99%. This study demonstrates the effectiveness of mangroves in protecting against wind and waves.



Figure 1. Examples of mangroves and their disaster preparedness, (a) mangrove plants, (b) mangrove habitat, (c) the 2004 Indian Ocean tsunami, (d) Sernarthorpe fishing village.

1.2. Baffle group structure based on debris flow control

As a common geological disaster, debris flow brings substantial economic losses to human society. Debris flow has a higher capacity than water flow, and its fluid binary phase containing soilds (rocks and soils) is characterized by high kinetic energy and high impact force [6,7,8]. The intense scouring generated by debris flow movement can lead to drastic changes in the ditch bed, causing ditch bed abrasion and ditch bank collapse. It will be increasing the source of material to recharge and increase the scale of debris flow.. The disaster cause serious harm to towns, roads, water channels, farmland, forests and other infrastructure[9]. It also has a tremendous impact on people's lives [10,11]. Therefore, it is of great socio-economic and ecological significance to develop and design management engineering products that can effectively mitigrate debris flow. The purpose of this study is reduce disaster destructive power and improve the safety of downstream protection objects.

Debris flow control engineering mainly includes water inpoundment, storage, drainage, and ecological engineering [12]. inpoundment and storage engineering can significantly reduces the debris flow hazard by intercepting the solids in the debris flow, which can make the loose solids do not participate in the movement. Among them, the baffles group is the widely used form of engineering structure in practical engineering [13,14,15,16]. Fig. 2(a-b) shows that array of baffles is a structure in which multiple baffles are arranged and combined according to some specific rules [14,16]. The baffles consctructed by low-profile reinforced concrete, which can slow down debris flow by increasing the roughness along the flow direction [17].

Some of the area of outstanding natural beauty in China have complex natural conditions which led to frequent debris flow [18] (Figure 2(c-d)). While the natural ecological

environment in these areas is beautiful, the traditional baffle groups used for debris flow control that are usually with simple and rough appearance will destroy these landscapes[19]. The traditional baffles group has not been designed by low-carbon and environmentally-friendly concept. At the same time, the existing baffles is mainly made of cement, which is highly alkaline and generally has high carbon emissions and pollution problems. To sum up, innovative baffles need to pay attention to the ornamental, aesthetic, low-carbon, and sustainable development of the design of debris flow prevention and mitigation projects. So the design of disaster prevention and mitigation projects and nature can achieve a real sense of harmony and unity.



Figure 2. Existing baffles and mudslide hazards in natural landscapes (a) Array of baffles in Hong Kong [20], (b) Array of baffles in mainland China [21], (c) Damage to the landscape from the Jiuzhaigou mudslide disaster (https://www.jiuzhai.com/news/scenic-news/6686-2019-07-22-10-37-47), (d) Damage to roads from the Jiuzhaigou mudslide disaster (http://news.huaxi100.com/show-226-799121-1.html).

1.3. Current status of bionic product design research

1.3.1. Overview of Bionics

The concept of bionics was firstly introduced by Dr. Steele at the first World Congress of Bionics in the 1960s [22]. Bionics is the science of constructing technological systems that mimic the principles of biological systems. It used to make artificial technical systems with characteristics of biological systems or similar features. In this scenario, Bionics represents an alternative tool for designers. It means a multidisciplinary science that researches the principles, properties and mechanisms of natural systems (structures, processes, functions, organizations and interrelations), with the aim of applying them in the development of new products or solving technical problems that may arise during project-phase[23].

Through billions of years of evolution and natural selection, nature has developed optimal morphological structures, efficient material metabolism recycling systems, and precisely controlled and coordinated processes. Bionics provides new design ideas, working codes, and system components for various research fields based on engineering technology by studying natural biological systems' structure, traits, principles, behavior, and interactions. Bionics in the research field includes structural Bionics, morphological Bionics, mechanical Bionics, mimetic Bionics, etc. [24].

1.3.2. The application of bionics in product design

Bionics-based product design is generally a creative approach to make such products more effective by drawing on the structure, form, texture, and function of plants and animals combined with the functional characteristics of the design object. [25].

Bionic product design is divided into four main types of design: morphological bionic, material bionic, structural bionic, and functional bionic [26]. Figure 3 is the summary and analysis of bionic design types and features. Structural bionic and functional bionic are more important in engineerigng. Structural biomimetic design is the analysis of the structural characteristics of natural organisms. The using of this structure can make products practical and aesthetically pleasing. Functional bionic design studies the applicable objective principles of natural microorganisms to gain inspiration for optimizing product performance.

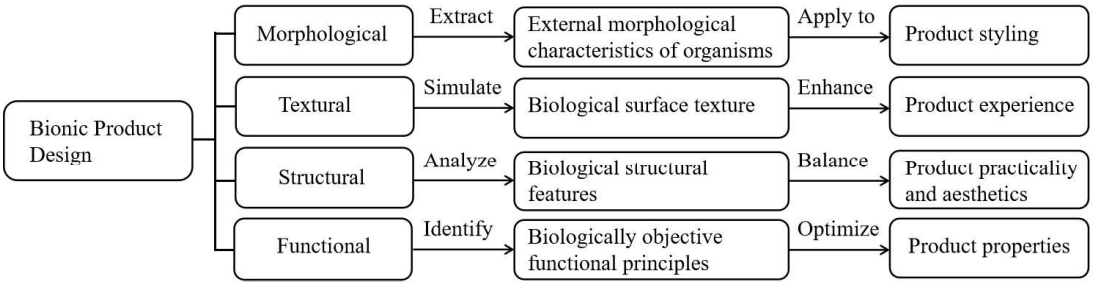


Figure 3. Summary and analysis of bionic design types and characteristics.

1.3.3. The application of bionics in product design

Bionic product design encompasses various fields, including everyday utensils, commodity packaging, office equipment, sports equipment, architectural spaces, and mechanical equipment. Nendo's Peggy money jar is based on functional bionic design[27], which taking the characteristics of a pig and making it into a jar in the shape of a pig's snout (Fig.4(a)). MUJI designer (Naoto Fukasawa) used material texture bionics[28] to mimic the color and texture of fruits (bananas, strawberries, and kiwis) to achieve a new design juice box (see Figure. 4(b)). The pangolin backpack [29] designed by Uriel Serrano is a structural bionic design with a shell that mimics the structure of the pangolin's keratin scales. The pangolin chair also refers to the shape of the pangolin, making it easier to store and fold, which can keep the user away from outside noise(Fig. 4(c).. The German company Festo has optimized the telescoping and flexibility of its robotic arm based on the structure of an elephant's trunk, allowing it to carry heavy loads more flexibly[31] (see Figure. 4(d)). The skull structure of the bird was found to be very light and highly impact-resistant. It was used in energy-efficient bio-building materials [32] (see Figure 4(e)). The LEX wearable bionic chair references the skeletal structure [30] to meet the user's need to be able to sit down at any times (see Figure 4(f))



Figure 4. Application of bionics in product design, (a) Peggy money jar, (b) MUJI juice box, (c) pangolin backpack, (d) Festo robotic arm, (e) Energy efficient biological building materials for the bionic bird skull structure, (f) LEX wearable bionic chair.

1.4. Overview of the development of bionic product design in engineering

Bionic product design has a long history of research and application in the engineering field. It mainly extract biological characteristics through four kinds of bionic design such as morphological bionic, material texture bionic, structural bionic, functional bionic.of At the end of the 20th century, it was discovered that the bullet-shaped nose of a train pushes the air in front of it at high speed through narrow lanes, creating a sonic boom effect that produces noise far over environmental standards. To solve this problems, Japanese engineering designers modified the bullet-shaped nose of a train by mimicking the beak section of a kingfisher [33], resulting in a 10% increase in speed, a 15% reduction in power consumption, and a significant reduction in noise levels (see Figure 5(a)). In the early 21st century, the Osaka Institute of Technology in Japan designed a serrated needle tip that mimics the mouthpiece of a mosquito. Unlike conventional cylindrical syringes, the central needle tip is provided with two subtle outer jagged strips next to it, which can significantly reduce the pain of lancing into the human body [34]. This is due to how the mosquito's mouthpiece touches the body so that it touches as few nerves in the human skin as possible, thus reducing the pain the person feels (Figure 5(b)). Omni-ID's company has created radio frequency ID tags by mimicking the subtle laminar structure on the wings of a blue butterfly. Using a series of delicate metal pieces to gather and alter the incoming radio waves to reflect a clear signal as a remote identification [35]. Because the laminate structure on the wings of this butterfly reflects sunlight from different angles, creating dazzling colors (Figure 5(c)). In 2020, Ben-Gurion University in Israel developed and designed AmphiSTAR. This new high-speed amphibious robot enables high-speed swimming and running on the water surface and crawling on the ground through a bionic snake monster lizard[36] equipped with four propellers and a pair of buoyancy tanks on the bottom. As the snake monster lizard has elongated toes, the soles of its feet are covered with scales. And the air bubbles created when the rankings come into contact with the water surface do not break the balance of surface tension, helping the lizard to run at high speed (see Figure 5(d)). The Bionic concept car from Mercedes in 2022 uses the growth principles of trees and bones[37] to reduce the material in the less stressed areas and further strengthen the fabric in the more loaded areas until the weight of the body is reduced by around 30% while maintaining stability, crashworthiness and driving experience. Both trees and bones are light but strong, with trees adding weight at important stress points and bones removing non-essential materials where they are not needed, achieving maximum robustness with minimal material (see Figure 5(e)).

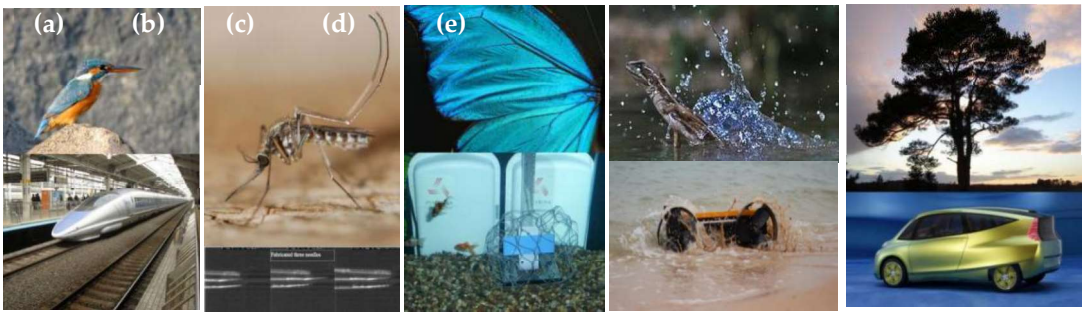


Figure 5. Application of bionics product design in the engineering field, (a) the Bionic kingfisher beak train head, (b) the zig-toothed tip of a Bionic mosquito mouthpiece, (c) the Omni-ID remote identification system, (d) the new high-speed amphibious robot AmphiSTAR, (e) the "Bionic" concept car launched by Mercedes.

Currently, bionics-based product design in the engineering field mainly involves transportation engineering, medical engineering, electrical engineering, mechanical engineering, and automotive engineering, but the field of geotechnical engineering is rarely applied and needs to be studied in depth comprehensively and systematically. This study will first extract the functional elements of mangrove plants through the six elements and ten steps product bionic design method. Secondly, build a decision target solution model based on hierarchical analysis (AHP), arrange and select mangrove bionic-related design elements, and build a geometric structure model. And compare and test its performance through numerical simulation. The final design will be a practical solution for designing disaster prevention products applicable to natural scenic areas.

2 Research Methodology and Design Process

2.1. Product bionic design concept

2.1.1. Six Elements and Ten Steps product bionic design method overview

Product bionic design is a product design method inspired by thinking about natural organisms and is based on extracting, analyzing, and imitating the structure, function, and form of living organisms to achieve innovative designs.

The Six Elements and Ten Steps systematic bionic design method, based on product bionic design theory, begins with a detailed analysis of the six elements of the bionic prototype: form, structure, texture, color, function, and system, which explores core reasons for an exceptional performance of the bionic prototype and extract the key features. The Six Elements and Ten Steps product bionic design methodology represents a widely applied design methodology that embodies a symbiotic and harmonious relationship between product design and bionic design. The design process is illustrated in Figure 8, where the six elements are form, structure, texture, color, function, and system, and the overall design process is divided into ten steps.

(1) Clarify the demand for product performance optimization. Analyze the current state of research according to the subject's background, explore the problems of similar products, and clarify the specific needs for product performance optimization.

(2) Compare and analyze similar bionic prototypes. Based on the bionic design concept, collect a variety of creatures and sort them out.

(3) Selecting the best bionic design prototype. Based on the achievement of the target performance, we compare the alternative bionic prototypes by listing the similarities associated with the creatures and finally select the bionic object with the best match.

(4) Dismantling the six core elements of the prototype. The six core elements of the biomimetic object, namely form, structure, texture, color, function, and system, are dissected in detail.

(5) Exploring the reasons for achieving the target performance. Based on the analysis of the six elements of the biomimetic prototype, the core elements of performance are explored, and the core reasons for achieving the target performance are investigated.

(6) Establish a chain of element-performance relationships. Establishing relationships between elements and target performance in balance regulation, immune resistance, supply support, information exchange, etc.

(7) Extracting critical features of relevant elements. Using hierarchical analysis to derive the details with the highest weights, extract the bionic key features from them, and modify the construction of multiple geometrized structural models.

(8) Simulation experiments to evaluate the effect of the model. Through numerical simulation and other scientific experimental methods, test the performance of the geometrical structural model, compare and analyze the experimental results, and select the best structural model from them.

(9) Adjustment of design elements according to the project. The design elements are further adjusted to be transformed into the product shape, which combining other design principles, such as environmental integration, scientific feasibility, artistic aesthetics, and practical orientation.

(10) Complete the target performance-oriented solution. Use design tools to establish product models and optimize and upgrade design concepts, structural shapes, colors and materials, functional applications, market values, and other aspects to finalize the bionic product design scheme.

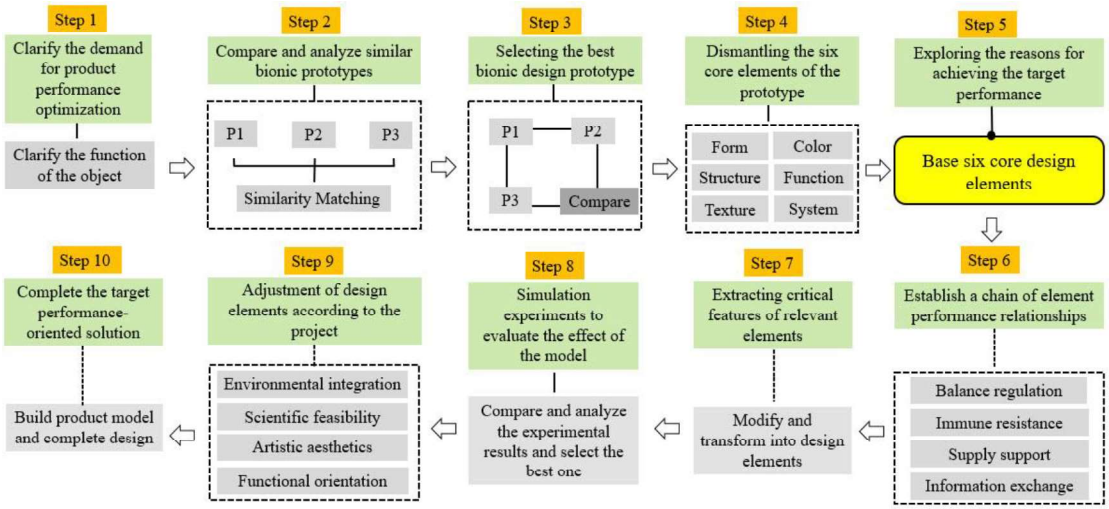


Figure 8. Six elements and Ten steps system bionic design method.

As the special growing conditions limit the mangrove planting area, it can only grow in the mudflats growing in the junction zone of land and sea.The mangrove has the function of wind and wave control. If the existing baffle structure can be optimized based on mangrove bionic, it will effectively protect debris flow. The application of mangrove wind and wave prevention functions in nature reserves and tourist attractions should be considered in the product design.

At the same time, the mangrove forest has strong natural ecological ornamental properties, and the bionic design needs to be both practical and aesthetic to realize the harmonious design of disaster prevention and mitigation project and the natural environment.

2.2. Analytic Hierarchy Process method

2.2.1. Overview of Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a practical and effective multi-criteria decision-making method that expresses and processes human subjective judgments in quantitative form, which was proposed by Professor Thomas L. Saaty, an operations researcher, in the early 1970s. Its combination of qualitative textual expression, quantitative numerical comparison, and systematic and modeled analysis of samples through

mathematical models, can effectively avoid the subjective one-sidedness of demand transformation when analyzing complex problems of decision-making.

2.2.2. Bionic design and hierarchical analysis

The bionic design needs to analyze and extract diverse design elements from the bionic prototype's morphology, structure, texture, color, function, and system aspects. The hierarchical analysis method is suitable for analyzing and comparing multiple elements. Since bionics has an extensive application in the design field, a hierarchical analysis method applicable to bionics is introduced based on the traditional hierarchical analysis method for subsequent in-depth research. To acquire the bionic design elements, the appropriate steps need to be adopted as follows: firstly, the core reasons for the mangroves' wind and wave protection function are explored by detailed analysis of mangroves from all aspects of morphology, color, structure, texture, process, and system, and the key features are extracted. Finally, the weight values of all the bionic design elements are calculated and arranged from highest to lowest. A scientific and reference result is obtained, which is applied to the Analytic Hierarchy Process of bionics, see Figure 9.

2.3. Analysis of the product design process based on mangrove bionics

The design method was shown in figure 10. This kind of method was adopted in this study, which combined with the AHP method to build a hierarchical structure model, calculate the target weights of design elements, filter and sort the design elements, get the core design elements and create a geometric bionic structure model. Then the best design case can be selected through a numerical simulation experiment, corrected, and transformed into product modeling. Finally, the design scheme is finished. The innovative design mode enhances the design efficiency, optimizes the product performance, and maximizes the product engineering effect. The design process is shown in Figure 10. divided into the following seven steps.

1) By analyzing the mangroves from morphology, structure, texture, function and system aspects, we explore the core reasons for mangroves' wind and wave protection function and extract the key features.

2) In-depth analysis of each key feature, clarify the relationship between the prototype features and the realization of wind and wave protection performance and modify and transform them into clear bionic design elements.

3) AHP was used to transform the mangrove bionic design elements into a recursive hierarchical model. A judgment matrix was used to quantify the design elements using mathematical methods. It selects the key factors determining mangroves' wind and wave protection performance.

4) To rank and select the total weight values of all mangrove bionic design elements and analyze and understand each aspect.

5) Based on the core features and design elements of the bionic design, make several prototypes of the core structure of the product design

6) To achieve the scientific feasibility of disaster prevention and mitigation performance, the comparative analysis of the blocking effect of different structural models is conducted through numerical simulation. The structural model with the best performance is selected.

7) Combining the design principles of environmental integration, scientific feasibility, artistic aesthetics, and practical orientation, the product shape based on the optimal performance structural model is further modified and beautified to complete the target performance-oriented bionic design scheme.

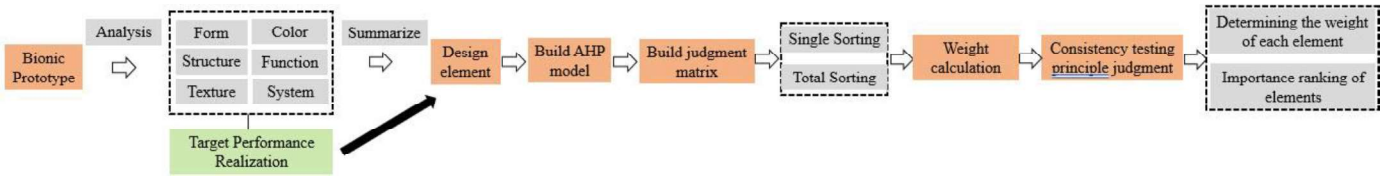


Figure 9. AHP method suitable to bionics.

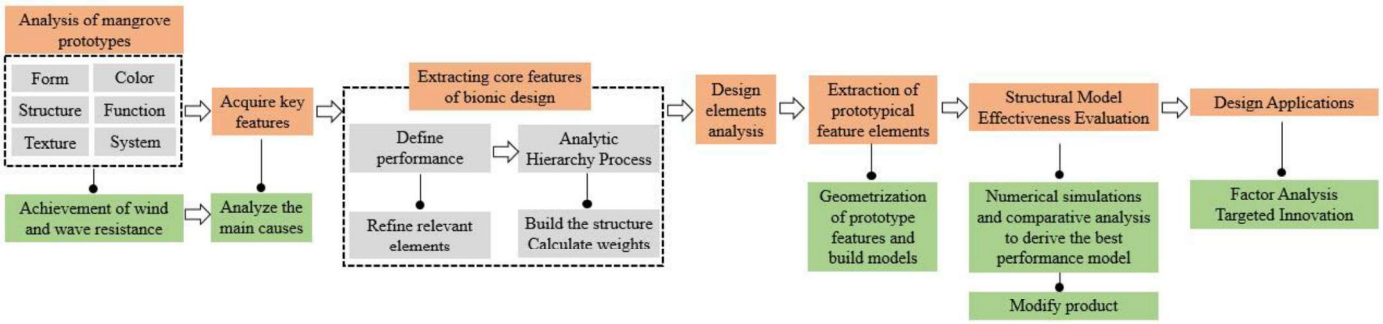


Figure 10. Design flow chart of disaster prevention and mitigation structure products based on mangrove bionics.

3. Design Process

3.1. Selection of mangrove characteristics

The six elements (morphology, structure, texture, color, function, and system) of mangrove forests were selected to analyze the core reasons for wind and wave protection. Based on the "six elements and ten steps" system bionic design method, the critical features for disaster migration extracted.

3.1.1. Analysis of "six elements" of mangroves

(1) Morphology, the tidal zone is a gently sloping terrain, and the inundation depth of mangrove plants varies. Mangrove plants are often single-optimal communities with a simple spatial structure and a green or gray-green to silver-grey appearance, with a forest height of 1-30 m. In addition, mangrove plants have a unique aerial root and strut root morphology. Due to anoxia and tidal flushing, tree species develop aerial roots, strut roots, and respiratory roots, such as plate-like roots, finger-like roots, knee-like roots, and snake-like creeping roots.

(2) Structurally, roots, trunk, branches, and leaves are the main constituent structures of mangrove plants. The root system is divided into respiratory, strut and aerial roots, forming a solid support for mangroves in the mudflat. The roots of mangrove plants tend to grow close to the surface, either as horizontally distributed cable-like roots or as surface roots exposed on the surface. Most plate roots and arching strut roots growing from the branch trunks are embedded in the mudflats to expand their holding capacity and keep the plant stable. Finger-like aerial roots are specially adapted to the mudflat environment, growing from the roots and drooping downward from the branches to expose on the beach floor. The shoot-like respiratory roots that travel across the ground, knee-shaped or vertically upward, facilitate oxygen uptake and are used for aeration at low tide or even when the wave is submerged. Due to the large number, deep roots and far spread. With the reason mentioned above, the mangrove plants can stand firm on the soft and drifting sandy mud.

(3) In terms of texture, the bark and trunk of mangrove plants show the basic texture of shrubs.

(4) In terms of color, the appearance of mangrove plants is green or gray-green to silver gray. Because it is rich in mono-tannic acid, it is reddish-brown after oxidation in the air, so the trees are often reddish-brown after being cut or felled, which is also the origin of the name "mangrove."

(5) Functional aspects: The developed root system has a huge biomass composition. The developed root has a serious of functions such as respiration and transmission of oxygen, reduce the power of the waves. The aerial roots on the ground and the underground roots exchange gas with each other so that they do not get stuck in the mud and suffocate due to lack of oxygen, ensuring that the mangrove plants need proper oxygen and respiratory needs to survive. At the same time, the root system fastens the mudflat sediment and reduces the silt reflux rate.

(6) Systematically, the aeration structure of the aerial roots makes them have strong permeability and suction ability. It can absorb oxygen from seawater. The bark is rich in tannins to assist in infiltration and corrosion protection. The release of tannins from seawater reduces the alkalinity of seawater. The leaves are succulent and thick, covered with a layer of wax to prevent water loss. The leaves contain salt-retentive tissue, so that excess salt can be secreted through the salt glands of the leaves.

3.1.2. Analysis of the causes of wind and wave protection in mangroves

Based on the above analysis of the six elements, it can be concluded that the elements related to wind and wave protection are mainly morphology, structure, and system. The key features of morphology are well-developed root system, dense canopy and mono-optimal community. The key features of structure are aerial roots, strut roots and respiratory roots. The key features of the system are aeration and water absorption system, infiltration and antiseptic system and salinity tissue system.

3.2. Primary and secondary analysis of mangrove bionomic design elements

3.2.1. Calculation of evaluation level index weights

According to the results of the above study, the main indicators of mangrove bionomics contain: morphology, structure, and texture. According to the results of the feature analysis, the importance ranking criteria of mangrove bionic design are established, which are shown in Table 1.

Table 1. Evaluation index of mangrove bionic design.

	First level indicators	Second level indicators
Mangrove bionic design element (U)	U1: Form	U11: Developed root system, U12: Individual Clusters, U13: Dense canopy of forest
	U2: Structure	U21: Pillar root, U22: Aerial roots, U23: Breathing root
	U3: System	U31: Ventilation and suction system, U32: Permeation and corrosion protection systems, U33: Salt-secreting tissue system

Regarding the weights of the above indicators, the expert questionnaire method was used for this purpose. In this study, the weights of the secondary indicators were calculated as an example. It is assumed that there are L experts evaluated, and questionnaires are conducted based on the Delfeld method. The ranking matrix is obtained based on the statistical results and is noted as A=(a_xi)_(L×M) (x=1,2,…,L,i=1,2,…,M).

After obtaining the experts' scores, the entropy theory is then used to calculate their entropy values. The specific steps are as follows:

(1) Calculate the subjective average recognition degree by the affiliation degree function formula:

$$b_{xi} = -\frac{\ln(h-a_{xi})}{\ln(h-1)}, h = M + 2 \quad (1)$$

where the matrix of affiliation is B=〖（b_xi）〗_(L×M), where b_xi is the affiliation degree of a_xi, then the average awareness degree b_i of all experts for the indicator i is:

$$b_i = (b_{1i} + b_{2i} + \cdots b_{Li})/L \quad (2)$$

(2) Define awareness blindness, denoted as Q_i, such that:

$$Q_i = \frac{|\max(b_{1i},b_{2i},\ldots,b_{Li}) - b_i + \min(b_{1i},b_{2i},\ldots,b_{Li}) - b_i|}{2} \quad (3)$$

(3) The overall awareness of experts for each indicator is denoted as r_i, then：

$$r_i = b_i(1 - Q_i) \quad (4)$$

Then the weight of the ith indicator among the peer indicators is：

$$w_i = \frac{r_i}{\sum_{i=1}^{M} r_i}, \omega_i > 0(i = 1,2,\ldots,M) \quad (5)$$

According to the above theory, taking the mangrove bionic prototype targeted in this study as an example, the weights of each of its indicators can be calculated according to the expert scoring method, and the weights of the secondary indicators in this study can be determined, as shown in Table 2.

Table 2. Weight of secondary indicators.

Second level indicators	Weight
U11: Developed root system	0.8
U12: Individual Clusters	0.1
U13: Dense canopy of forest	0.1
U_{21}: Pillar root	0.6
U_{22}: Aerial roots	0.3
U_{23}: Breathing root	0.1
U_{31}: Ventilation and suction system	0.5
U_2: Permeation and corrosion protection systems	0.4
U_{33}: Salt-secreting tissue system	0.1

According to the above weight distribution, all the secondary indicators can be assigned according to major, medium, and minor impact indicators, and their specific indicator descriptions are shown in Table 3.

Table 3. The index and description of mangrove bionic design.

Element	Key impact indicators	Moderate impact indicators	Minor impact indicators
Form	Developed root system	Dense canopy of forest	Dense canopy of forest
Structure	Pillar root	Aerial roots	Breathing root
System	Ventilation and suction system	Permeation and corrosion protection systems	Salt-secreting tissue system

Table 4 shows the range of scores given according to the importance of each secondary indicator. The lower the score, the lower the importance. By scoring the second-level indicators, the final score of the first-level indicators is calculated based on their weighting. The formula for scoring the first-level indicators is shown below.

$$P = 0.8 \times p1 + 0.1 \times p2 + 0.1 \times p3 \quad (6)$$

$$W = 0.6 \times w1 + 0.3 \times w2 + 0.1 \times w3 \quad (7)$$

$$C = 0.5 \times c1 + 0.4 \times c2 + 0.1 \times c3 \quad (8)$$

Table 4. Score of each secondary indicator.

Symbol	Secondary Indicators	Scoring interval	Final score for Level 1 indicators
p1	U_{11}:Developed root system	[90,100]	P
p2	U_{12}: Dense forest canopy	[80,90]	
p3	U_{13}:Mono-optimal communities	[0,80]	
w1	U_{21}: Pillar roots	[90,100]	W
w2	U_{22}: Aerial roots	[80,90]	
w3	U_{23}: Respiratory roots	[0,80]	

c1	U_{31}:Aeration and water absorption systems	[90,100]	
c2	U_{32}:Osmotic and preservative system	[80,90]	C
c3	U_{33}: Salt-secreting tissue system	[0,80]	

Based on the final scores, the importance distribution of this bionic design can be derived from Table 5, which suggests some methodological guidance for this design.

Table 5. Mangrove bionic design quantified by importance of indicators.

Risk class	Name	Range of quantification
Ⅰ	Most Important	(80, 100]
Ⅱ	Moderately important	(50, 80]
Ⅲ	Least important	(0, 50]

3.2.2. Analysis of design elements

According to the calculation results, the importance of the prototypical features of the design elements extracted from the bionic design of the mangrove plant based on its wind and wave protection properties is ranked as follows: structure > morphology > system. The design solution needs to weigh the importance distribution of each feature and related elements. According to the secondary weights, the most important structural aspects are the strut and aerial roots, with the respiratory roots being a secondary consideration. Morphological elements are most important in terms of developed root systems and dense canopies, with mono-optimal communities being a secondary consideration. Systematic aspects scored low and were not considered in this design.

Combining structural and morphological features, it can be concluded that the well-developed and diverse root system of mangrove plants is the key to this bionic design. The root system's critical structural and morphological features need to be extracted, revised, adjusted and translated into design elements by combining the principles of scientific feasibility, practical orientation, low carbon, environmental protection, natural integration, and artistic aesthetics.

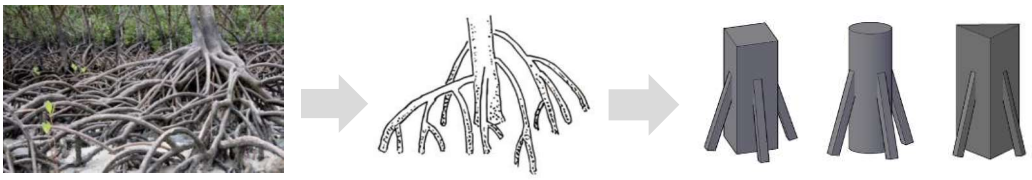
3.3. Numerical simulation experiments on disaster prevention and mitigation structures

3.3.1. Introduction to EDEM software

The Discrete Element Method (DEM) is a material analysis method for discrete particle bodies. EDEM is a modeling software based on DEM that can be used for the simulation and analysis of the production process of particle handling and manufacturing equipment in industrial production. EDEM's powerful simulation capabilities allow for a good simulation of debris flow particles impacting different groups of piles.

3.3.2. Root system feature extraction

Based on the analysis of the design elements, the morphological and structural characteristics of the root system of the mangrove plant were extracted and summarised in a linear diagram. The experimental properties combined with numerical simulation were also considered and condensed into three geometric shapes: square column, round column, and triangular conical column, while the initial optimization of the traditional pile groups was realized to form the basic structure of the new pile groups, and the extraction transformation process is shown in Figure 11.



(a) (b) (c)

Figure 11. Extraction and transformation of root characteristics of mangrove plants, (a) Mangrove root system, (b) Linear diagram of root morphology and structure, (c) Geometric structure condensation

3.3.3. Simulation device and test pile group type

The simulation device refers to the model of previous papers [37,38] and material parameters [39]. The test platform consists of five parts: material source box, chute, piling platform, platform side plate, and blocking group piles. The material box size, chute size mm, and the inclination angle is; piling platform size. The pile group uses three rows of piles with a side length of 50mm, a pile height of 180mm, a blocking distance of 400mm (the distance between the foot of the chute slope and the first row of piles), and a row spacing of 70mm row spacing of 50mm and 90mm. The 3D model created is shown in Figure 12.

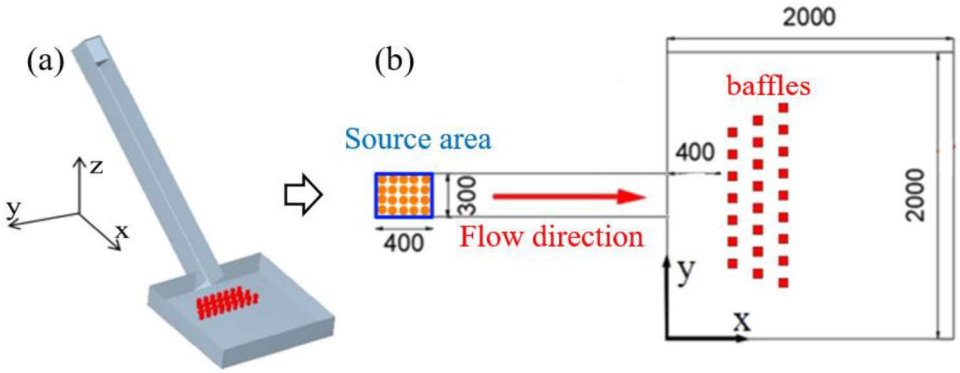


Figure 12. Extraction and transformation of root characteristics of mangrove plants, (a) Mangrove root system, (b) Linear diagram of root morphology and structure, (c) Geometric structure condensation.

To analyse the debris flow interception effect of the basic structure of different types of new baffles, the DEM simulation was used for investigation. The debris flow particles with a concentrated particle size distribution of 5-20 mm and a total mass of 60 kg as well as three new piles plus three conventional piles, the types of pile groups involved in the test are shown in Figure 13.

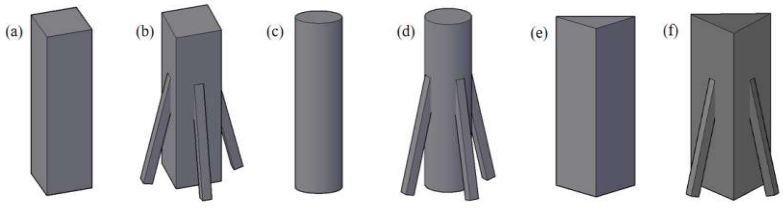


Figure 13. Pile group type, (a) Z1; (b) Z2; (C) Z3; (d) Z4; (e) Z5; (f) Z6.

Z1, Z3, and Z5 are conventional piles, and Z2, Z4, and Z6 are new bundles. A total of 12 sets of tests were set up to numerically simulate each of the six types of banks at two inter-pile opening distances.

3.3.4. Parameter setting

In DEM simulations, the physical parameters of the material need to be calibrated, which are the intrinsic parameters of the material and the contact parameters between the materials. The intrinsic parameters are the Poisson's ratio, shear modulus, and density, respectively, and the contact parameters are the static friction factor, rolling friction factor, and elastic recovery coefficient. The intrinsic and contact parameters of the material in this experiment were set by reference to the literature [39,40,41]. The particles, the chute, the block pile group, the area, and the platform side plates are considered rigid bodies. The deformation resulting from the particle-particle and particle-steel contact is not considered. Thus their elastic recovery coefficients are treated by taking the same value. The static and rolling friction factors between the particles measured in the literature [39] were referenced. Ultimately, after several tuning of the numerical simulation parameters, the material intrinsic parameters and the contact properties between the materials were determined, as shown in Tables 6 and 7.

Table 6. Material intrinsic parameters.

Material	Poisson's ratio	Density/(kg• m⁻³)	Modulus of shear/Pa
Debris flow granules	0.25	2100	8× 10⁸
Chutes (steel)	0.3	7900	7× 10¹⁰
Pile groups, pile areas and side panels	0.3	7900	7× 10¹⁰

Table 7. Contact properties.

Type of contact	Elastic recovery factor	Coefficient of static friction	Rolling friction coefficient
Pellets-Pellets	0.6	1.33	0.15
Pellets - Steel	0.6	0.453	0.05

3.3.5. Analysis of numerical simulation results

3.3.5.1. Motion process and velocity analysis

Figure 14 shows the velocity analysis and stationary accumulation process of debris flow particles impacting the Z1 pile group with a blocking distance of 400mm and an opening between piles of 90mm. As shown in Figure 3(a), at t=0s, the particle plant in the DEM produces particles, and the particles are in a stationary accumulation state under the blockage of the material box; at t=0.3s, the debris flow particles in Figure 3(b) start to collapse under the action of gravity, and a more obvious velocity stratification phenomenon occurs, with the leading edge particles having higher velocity while the trailing particles are still in the uninitiated stage, and this stage continues until Figure 14(c) in t=1.1s; in Fig. 14(d), the frontmost particle rushes to the foot of the slope, and its velocity decreases after hitting the bottom plate of the pile area, and produces the phenomenon of leap; due to the obstruction of the front-end particle, the speed of the following rear particles decreases and friction increases, and starts to slow down and slide in the pile area; some particles pass through the gap between the piles, and are blocked by the staggered pile group Some particles pass through the gap between the ridges and are blocked by the staggered group of banks, and the pile accumulates at rest in the pile area. The particles at the back end are obstructed by the stationary pile at the front end and disperse to both sides of the original path, as shown in Fig. 14(e). Eventually, the particles lose kinetic energy to complete the stationary pile in front of the group of mounds; after that, the subsequent particles decelerate and slide on the standing rise

until all particles in Fig. 14(f) stop moving, and the bank ends. In summary, the process of debris flow particles impacting the pile group can be divided into an initiation phase, an acceleration phase, a deceleration phase, and a blocking pile phase.

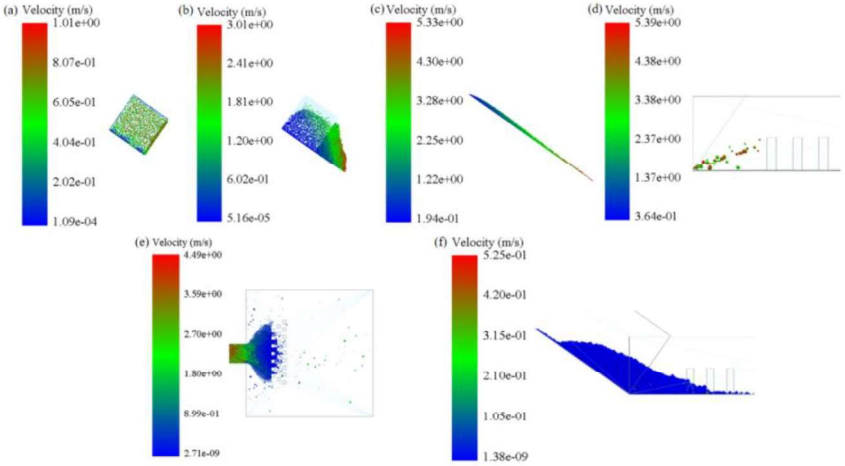


Figure 14. Impact of debris flow particles on a cluster of Z1 piles, (a)t=0 s；(b)t=0.3 s；(c)t=1.1 s；(d)t=1.3 s；(e)t=2 s；(f)t=4 s.

To investigate the effect of different types of baffles on the velocity of debris flow particles, a series of numerical studies were adopted in this paper. Six kinds of baffles with a set debris flow particle impact opening between piles of 90 mm were used as examples. In Figure 15, before t=1.3s, the maximum velocity of the debris flow is the same in all six cases due to the same working conditions. And the time required to reach the peak velocity is the same; after 1.3s, the debris flow particles start to be blocked by different blocking pile groups. The speed decreases to different degrees; after impacting the Z2 pile group, the rate is lower than Z1; after affecting the Z4 pile group, the velocity is lower than Z3. While after moving the Z5 pile group, the speed is higher than Z6. This indicates that the new piles Z2 and Z4 are more effective in reducing the impact velocity of the debris flow than the traditional piles Z1 and Z3. At the same time, Z6 does not have a better stopping effect than Z5.

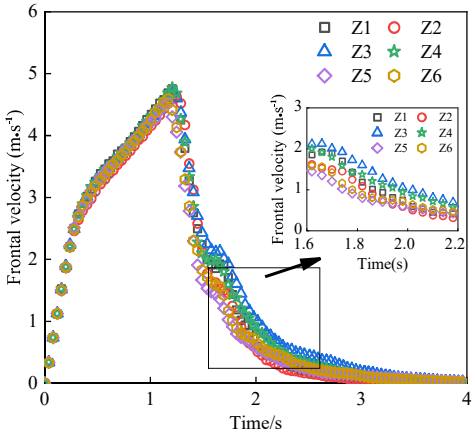


Figure 15. The effect of different pile groups on the particle tap velocity of debris flows.

3.3.5.2. Effect of different pile groups and inter-pile openings on particle accumulation patterns

To investigate the effect of inter-pile openings on the particle arresting effect of the debris flow, the accumulation area of the particle flow after impacting the same pile group at different inter-pile opening distances is plotted in Figure 16. Figure 16 shows that the debris flow completes the accumulation in front of the third row of piles of the six pile groups at either 50mm or 90mm inter-pile opening distance. In the traditional

pile group, the debris flow is stationary and accumulates close to the third row of piles, and all rows of ridges are fully utilized. While in the new pile group, the debris flow is stationary at a certain distance from the third row of piles with a 90mm inter-pile opening, which is since the debris flow when impacting. This is because when the debris flow affects the new pile group, the particular structure makes the first two rows of piles sufficient to intercept all the particles and have a better stopping effect. The above phenomenon shows that the six pile groups with 50 mm and 90 mm openings have a better-stopping effect on the debris flow. And the first two rows of the new pile group with 90 mm openings can achieve the same stopping effect as the three rows of the traditional pile group.

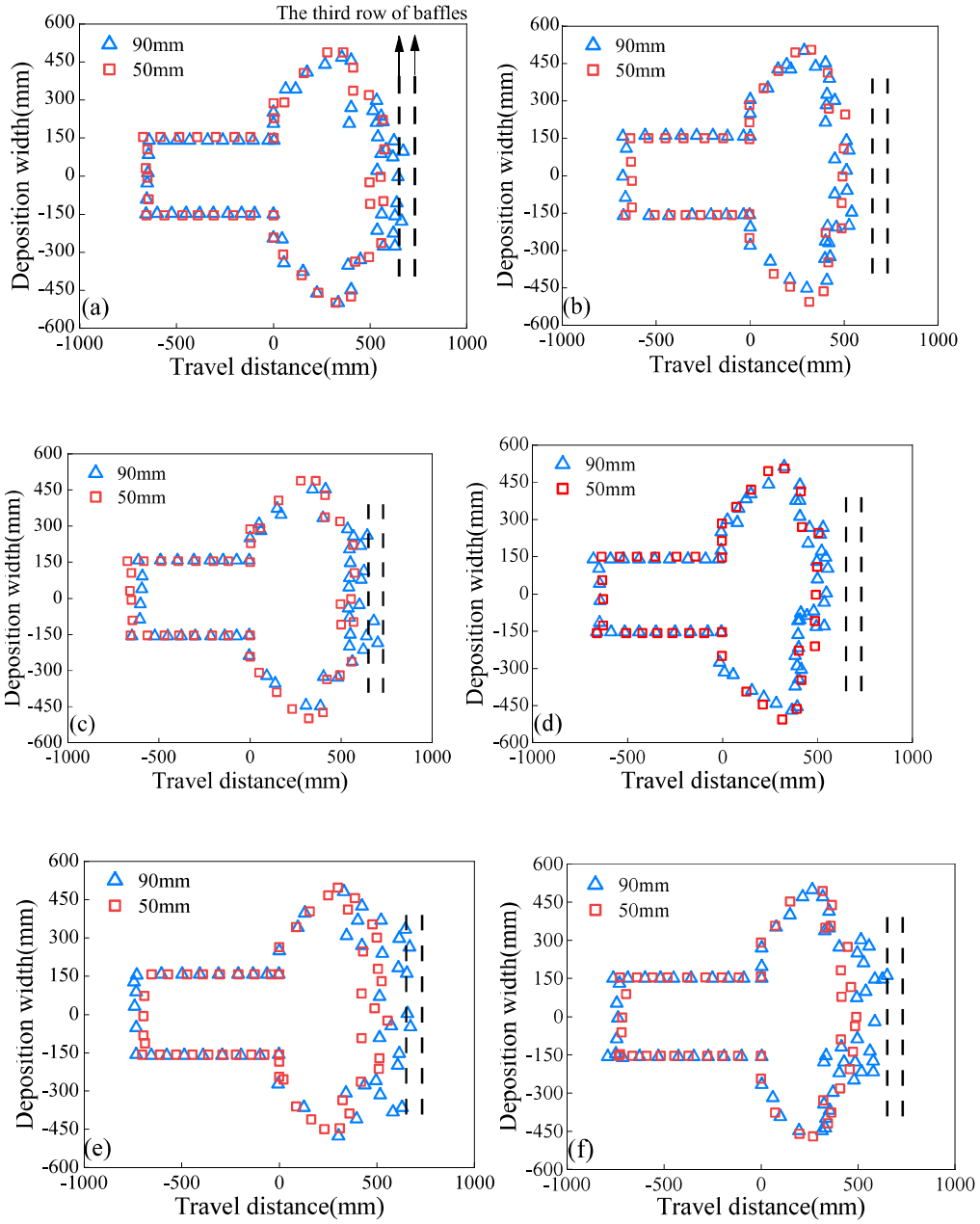


Figure 16. Influence of the distance between pile openings on the effectiveness of debris flow interception, (a)Z1,(b)Z2,(c)Z3,(d)Z4,(e)Z5,(f)Z6.

According to the analysis of the effect of pile type on the debris flow arresting development in Figure 17, it can be seen that all pile types have an excellent arresting effect on the debris flow. In general, the impact distance and pile width of debris flow particles in the pile area of different pile groups do not differ significantly. Fig. 17(a) For an

opening of 50 mm between piles, the accumulation areas of Z1, Z2, Z3, Z4, Z5, and Z6 are 628413, 582935, 658281, 586552, 581756, and 571577 mm2, respectively. Fig. 17(b) For an opening of 90 mm between piles, the accumulation areas of Z1, Z2, Z3, Z4, Z5, and Z6 are The comparison shows that the debris flow is less likely to accumulate under the new piles Z2, Z4, and Z6.

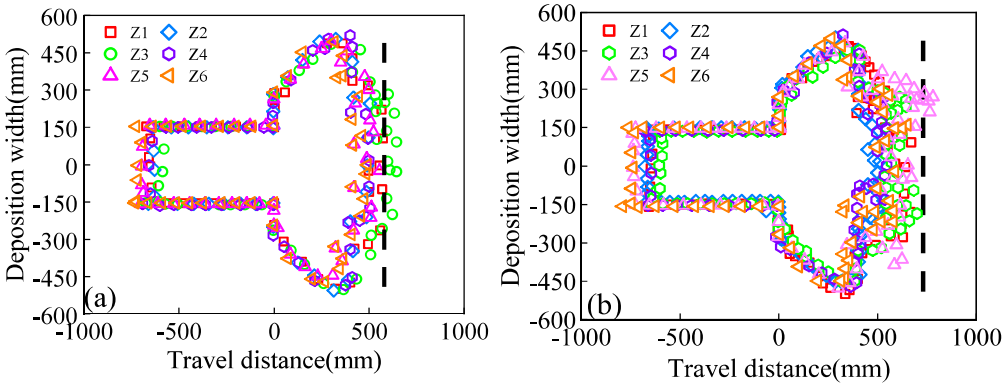


Figure 17. Effect of pile type on the morphology of the debris flow pile, (a) 50mm opening distance between piles, (b) 90mm opening distance between piles.

To investigate the influence of the pile type on the mass distribution of the accumulation area after the debris flow is stopped by the group of piles, as shown in Figure 18(a), six types of pile groups with 90mm openings between piles were selected, and a zone was set every 80mm along the slope, A1-A10 in order, and the particle mass of each site was obtained in the DEM, to analyze the law of different pile types on the mass distribution of the debris flow accumulation. From the analysis in Figure 18(b), it can be seen that the mass distribution of the debris flow is more or less the same after encountering the different pile groups, which increases and then decreases. At a distance of less than 400mm from the foot of the slope, mass of the debris flow in all areas of the pile is greater than that of the conventional pile group under the action of the new pile group; while at a distance of more than 400mm from the foot of the slope, the opposite trend is observed. This is because the new piles have a 'foot' that keeps more debris flow particles in front of the bank and less behind it. The Z2 and Z4 conditions have the lowest pile masses.

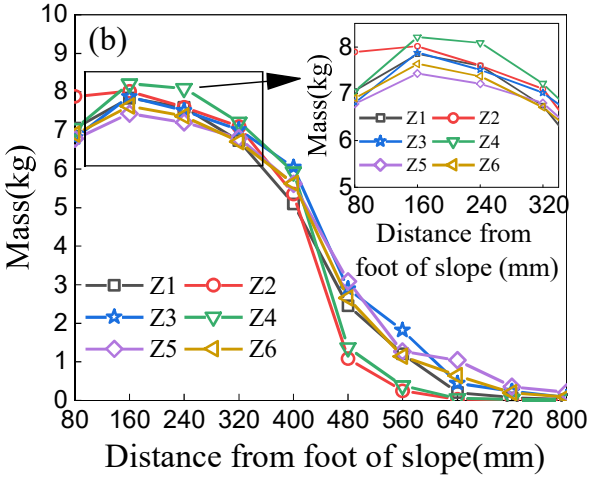


Figure 18. Influence of pile type on pile mass distribution, (a) schematic plan of mass calculation in the pile area, (b) influence of pile type on mass distribution in the pile .

3.3.6. Summary

Numerical simulations show that the Z2 and Z4 structures have the best blocking effect, i.e., the two geometric shapes of square and round columns in the main body, with the addition of a root-like base at the bottom, when the structure has the best performance. However, in terms of artistic aesthetics and bionic design principles, the round column is more straightforward to realize than the square column to achieve the visual effect of the product shape of this design project, and at the same time has more integrity. The transformation process of the product shape modification is shown in Figure 19.

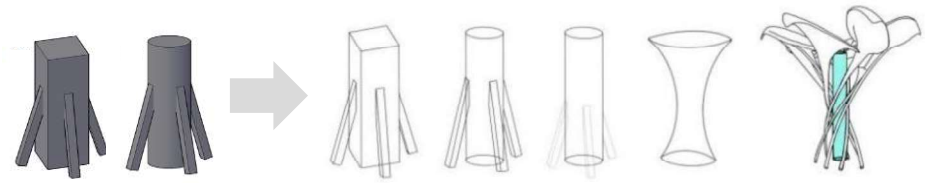


Figure 19. Product shape modification and transformation process.

3.4. Mangrove bionics-based design practice for disaster prevention and structural mitigation products

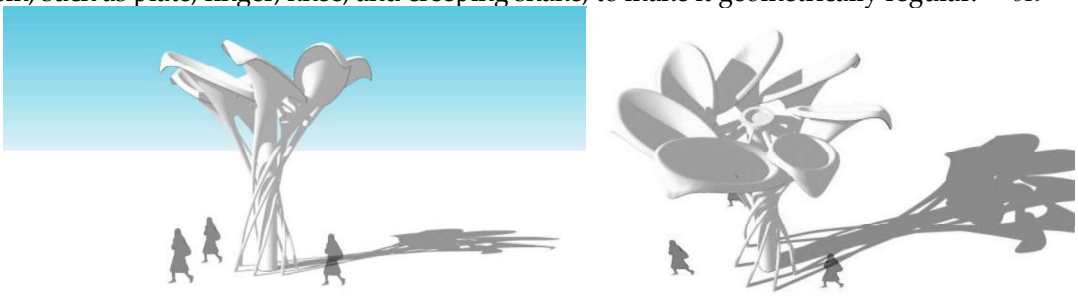
The final design case is based on the "Six Elements and Ten Steps" systematic bionomic design methodology to rank the design requirements of mangrove plants. The scheme is a modified version of an existing pile group based on a bionic mangrove root structure and forms to achieve a highly effective wind and wave-resistant decorative landscape. It also considers the natural ecological beauty of nature reserves and tourist attractions. It considers the ornamental, aesthetic, and environmental aspects of the design of the prevention and mitigation project so that the creation of the disaster prevention and mitigation project is harmoniously integrated with nature in the true sense.

3.4.1. Exterior design

The scheme focuses on its practical orientation and functional diversity. It contains the following three main items: the essential function of the engineering structure set up for disaster prevention and mitigation protection, the secondary part of creating a dynamic, open space, and the additional value of the brand marketing of the net attraction.

3.4.1.1. Structural shape

Firstly, two optimal effects of the pile group structure were selected through numerical simulation experiments to confirm its scientific feasibility. The overall mangrove plant structure is mainly a rotating structure with a hollowed-out effect in the circle space, which is dynamic and artistic, and Fig. 20(a) is the front view pic. The upper part of the structure is a floral bloom, the Fig. 20(b) is the top view pic. The lower part of the structure is a root system, which integrates various morphological features of the root system, such as plate, finger, knee, and creeping snake, to make it geometrically regular.



(a) (b)

Figure 20. Analysis of product modeling structure characteristics, (a) front view, (b) top view.

3.4.1.2. Colour material

The optimization of the structure of the barrier pile group is a revision of the design of the protective engineering that invades nature, respecting the ecological environment and the externally associated structural engineering system of disaster prevention and mitigation, trying to give it a new artistic life. The scheme's aesthetic quality is reflected not only in the lines of the form but also in the harmonization of the colors and the ecological and developmental outlook it embodies. As cement is highly alkaline and has a high carbon footprint, the central column and side pillar feet are replaced with an eco-friendly material, glutinous rice mortar, one of the green high-performance concrete materials. The upper 'petals' are made of colored acrylic with a clear and fresh texture, figure 21(a) is the daytime view. The edges are lit with spotlights for localized accent lighting to create a rich, colorful ambiance for the theme, creating an enchanting and hazy night scene, and figure 21(b) is the night view.



(a) (b)

Figure 21. Color and material presentation of products, (a) daytime, (b) night.

3.4.1.3. Overall style

The artistic and aesthetic nature of the overall style of the scheme is mainly reflected in the cultural concept, the environmental vision, and the resonance of ideas, which is a product of the thinking consciousness of "balancing engineering design and artistic aesthetics" and the spiritual concept of "harmonious coexistence between man and nature." The artistic tension is not reflected in the complex structural shape and color scheme but in the use of condensed and straightforward curves and harmonious color schemes to highlight the gesture of the product design. The primary benefit of mangrove botanical imitation, combined with the dynamic shape of flowers in bloom, brings it back to its true nature and allows the engineering design to be truly integrated into the environment.

3.4.2. Functional design

The scheme focuses on its practical orientation and functional diversity. It contains the following three main items: the essential function of the engineering structure set up for disaster prevention and mitigation protection, the secondary part of creating a dynamic, open space, and the additional value of the brand marketing of the net attraction.

3.4.2.1. Effectiveness of disaster prevention and mitigation protection

The mangrove bionic design with the core objective of optimizing the structure of the blocking pile group, the optimal pile group structure selected through numerical simulation experiments, and the artistic design processing and embellishment based on its simple geometric shape, to realize its engineering basis of mudslide disaster protection function as an essential premise.

3.4.2.2. Dynamic, open space creation

The top imitates the dense canopy of mangrove plants. It is also in the shape of a flower petal blooming, meeting the ornamental and, at the same time, available for visitors to rest, fully reflecting its environmental integration. At night, the illumination of

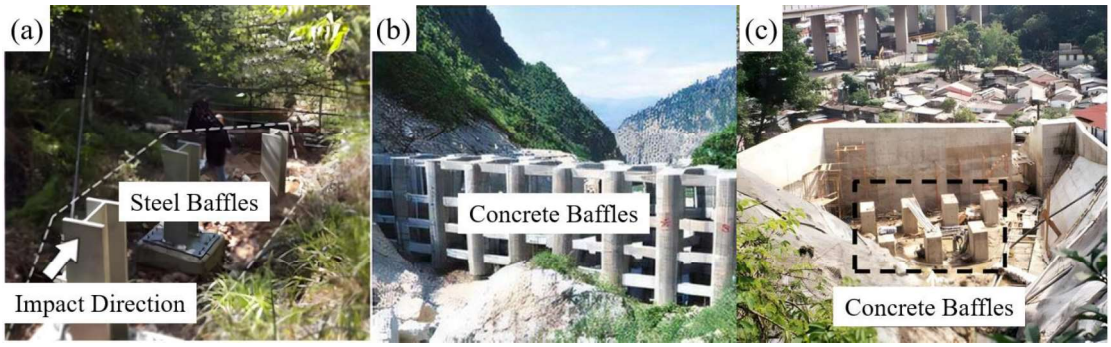
the "petal" edge creates a warm and romantic atmosphere, thus bringing a rich visual experience to the viewer. The different light intensities, color changes, and light shadows convey the viewer's feelings, strengthening the emotional expression of the product theme and expanding new ideas for the business model of nature reserves and tourist attractions.

3.4.2.3. Brand marketing of the Netflix attraction

The scheme has a strong sense of overall artistic modeling. In the internet era, it is in line with the trend of Netflix traffic in tourist attractions. It has the potential to develop into a scenic spot to attract traffic and publicity. At the same time, because of its design and applicability, it can be used as a photo-punching place in nature reserves and tourist attractions, guiding visitors to look at ecological issues with a developmental eye. Let the disaster prevention and structural mitigation products achieve their engineering governance efficacy based on the symbiotic sharing with nature, environment, ecology, humanities, economy, and brand. To realize the vision of harmonious co-existence of natural habitat, intermingling of societies, and economic effects of the brand.

3.4.3. Summary of the design scheme

The mangrove bionomics is the theoretical application kernel for the functional realization of the project design and the visual presentation subject of the design theme, which calls for people to actively examine the relationship between nature and human beings through the anthropomorphic and natural modeling presentation. The design has significant advantages over traditional pile groups in terms of scientific feasibility, functional orientation, low-carbon environmental protection, natural integration, and artistic aesthetics, and Figure 22 is the comparison. The double impact of emotion and visual feeling makes it come alive and gives it the language of the times. Only by combining engineering applications, artistic design, and the natural environment can we better promote the ecological and economic development of the creation of disaster prevention and mitigation structures.



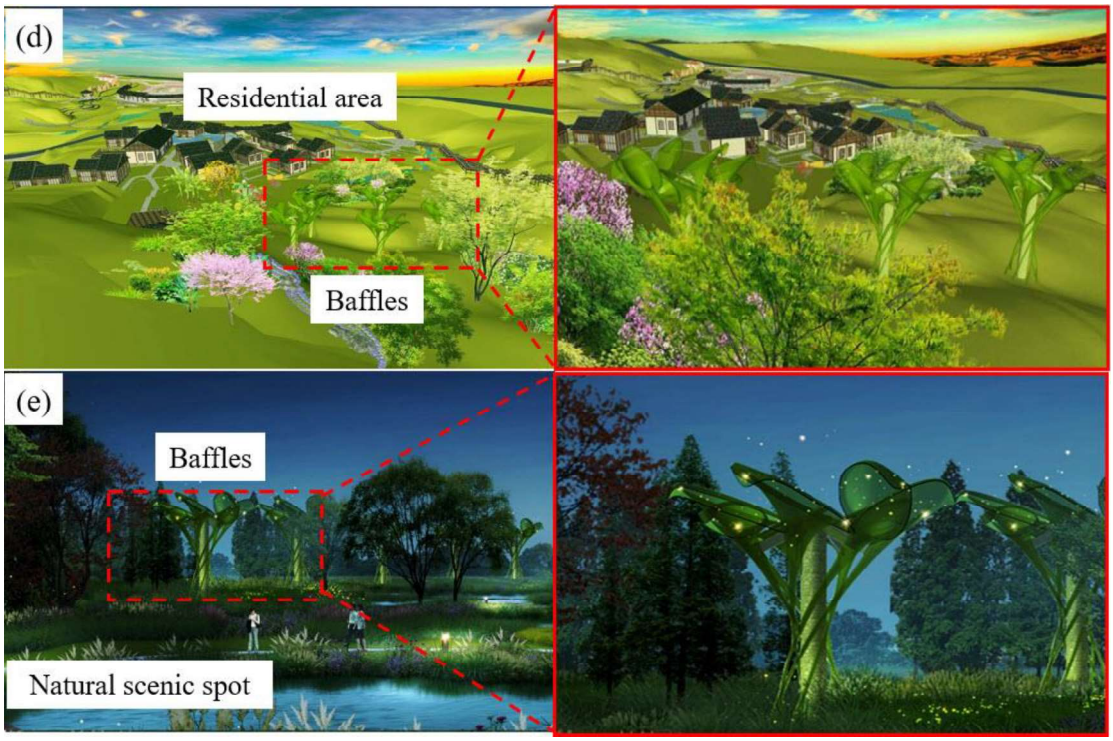


Figure 22. Comparison of traditional pile group application examples and design renderings, (a) traditional steel baffles in Hongkong, China, (b) traditional concrete baffles in China mainland, (c) traditional concrete baffles in Hongkong, China, (b) daytime effects of Mangrove baffles, (c) night effects of Mangrove baffles.

4. Discussion

This paper proposes a bionic engineering-based product design methodology, namely the "Six Elements and Ten Steps" product bionic design methodology, based on the bionic design of mangrove forests for disaster prevention and mitigation. By comparing the six elements of the bionic prototype - form, structure, texture, color, function, and system - with the strength of their relevance to the performance of the target, key elements are extracted and refined through hierarchical analysis. The core structural model is then constructed. Through experimental scientific methods such as numerical simulation to test, analyze and compare the degree of efficacy of each model, the optimal model is selected, optimized, and improved to shape the product. According to the project requirements, other functions and features of the product are improved with specific design principles and finalized design solutions. Based on the results, the following conclusions can be drawn:

(1)The mangrove bionic disaster prevention and mitigation product design is based on the integration of nature and is functionally oriented. Its functional advantages are the essential function of disaster prevention and mitigation, the secondary part of creating a dynamic recreational space, and the added value of creating a branding and marketing of an online attraction. At the same time, the design and material selection of the scheme take into account artistic aesthetics and low-carbon environmental protection and use mathematical modeling and experiments to run. The scientific feasibility effectively alleviates the existing disaster prevention and mitigation engineering problems of insufficient blocking, ornamental and environmental protection, and optimizing disaster prevention and mitigation engineering. It also proposes that the integration of "engineering," "design," "ecology," and "business" to form a value chain is the future trend of engineering. The future direction of bionic product design development is expected to achieve a win-win situation regarding social, ecological, economic, and artistic values. The product validates the feasibility of the "six elements and ten steps" product bionic design methodology and provides a reference for other related design practices.

(2) The "Six Elements and Ten Steps" product bionic design methodology is based on the perspective of bionic engineering. It attempts to propose a set of theoretical design frameworks in the form of a method to address some of the drawbacks of traditional engineering project design. The methodology specifies the elements and steps to be considered in the process of bionic engineering design. It helps designers to efficiently select key bionic elements and their advanced features, i.e., design elements, through the AHP while emphasizing the importance of scientific experiments in evaluation and comparison. In contrast, the interpretation of bionic engineering-based product design and the corresponding design strategies may vary significantly from one engineering application area to another, from one designer to another, and from one period to another. The design methodology still has some limitations regarding its general applicability in different engineering fields. Still, it can provide helpful theoretical support for most benign bionic design innovations.

(3) The mangrove bionomics-based design of the pile group structure has better debris flow dissipation characteristics than the traditional pile group structure. The particle accumulation mass after the baffles can be effectively reduced by 2~3 times, and the debris flow's accumulation area and tap speed are reduced to different degrees. The product has guiding significance for applying disaster prevention and mitigation in actual projects. Compared to traditional baffles groups, this structure is more aesthetically pleasing, has disaster prevention and mitigation functions, and is suitable for deployment in scenic areas.

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Informed Consent Statement: Not applicable for studies. Not involving humans.

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