Handbook of Ecosystem Restoration for Coastal Hazard Mitigation: Sandy Coasts

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Organizations and Personnel

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INTRODUCTION

Natural disasters are among the most pressing global challenges facing humanity today. To effectively address their severe impacts, approaches such as Nature-based Solutions (NbS) and Ecosystem-based Disaster Risk Reduction (Eco-DRR) have gained significant global attention. These strategies aim to leverage ecosystem services for disaster mitigation through the protection, restoration, and sustainable management of ecosystems, ultimately ensuring sustainable and resilient socio-economic development. These approaches are highly aligned with China's vision of ecological civilization and its modern principles of disaster prevention and mitigation.

In coastal areas, ecosystems such as salt marshes, oyster reefs, sandy shores, and seagrass beds serve as natural buffers, protecting against tides and waves while reinforcing embankments and safeguarding shorelines. These ecosystems act as "guardians of the sea," playing a crucial role in mitigating the risks of marine disasters. Through the ecological protection and restoration of coastal zones, the disaster mitigation functions of these ecosystems can be fully realized, enhancing the ability of coastal areas to withstand typhoons, storm surges, and other marine hazards. To guide practical work in this field, the Ministry of Natural Resources has launched a series of handbooks on coastal ecosystem restoration. These handbooks aim to integrate ecological benefits with marine hazard mitigation, focusing on the restoration of coastal salt marshes, oyster reefs, sandy shores, and seagrass beds. They offer detailed guidance on ecological baseline surveys, problem diagnosis, restoration objectives, intervention measures, and the entire chain of technical steps, including monitoring, evaluation, and adaptive management. Emphasizing science popularisation, practicality, and operability, the handbooks are concise and well-illustrated, providing valuable technical support for the scientific implementation of ecological disaster mitigation and restoration in coastal areas.

This series of handbooks has been developed with support from the Ministry of Finance and the International Union for Conservation of Nature (IUCN), to whom we express our sincere gratitude. We also extend our appreciation to the practitioners and experts dedicated to coastal zone ecological disaster mitigation and restoration.

Due to the limited time and resources available for the preparation of these handbooks, there may be unavoidable shortcomings. We welcome your feedback and suggestions for improvement.

CONTENTS

1.Scope of Application

This handbook presents details of the principles, technical procedures, and application processes for the ecological restoration of sandy coasts. It outlines the technical specifications and approaches for different tasks, such as conducting prerestoration status surveys, defining restoration objectives and methods, choosing restoration techniques, designing and implementing restoration projects, conducting postrestoration monitoring, evaluating effectiveness, and implementing adaptive management.

This handbook is designed for ecological restoration and hazard mitigation efforts on both natural and artificial beaches along China's sandy coasts. Other related projects may also find this handbook useful as a reference.

2.Terms and Definitions

The following terms and definitions apply to this technical handbook.

(1) Coastal zone

The zone where land and sea interact, extending from the furthest point that seawater can reach on land to the deepest point on the seabed affected by wave action. In a broader sense, the coastal zone can extend inland to the adjacent plain and seaward to the edge of the continental shelf.

(2) Coastline

The boundary between the land and sea, commonly referred to as the line delineating the land-sea interface at the mean spring high water in China.

(3) Sandy coast

A coastline predominantly composed of sand (or gravel) shaped mainly by wave action.

(4) Beach

A deposit of loose sediments formed by wave action and swash flows along the shore.

(5) Backshore

The area extending landward from the mean spring high water to where vegetation begins to grow or where there is a change in natural geographical features.

(6) Foreshore

The zone between the mean spring high water and the mean spring low water.

(7) Inshore

The area between the mean spring low water and the outer boundary of the breaker zone.

(8) Longshore bar and trough

Long, narrow sand ridges and accompanying troughs that align parallel to the shoreline. These may become exposed at low tide and can form a series of parallel systems at different water depths.

(9) Breaker zone

The area where incoming waves become unstable and break.

(10) Surf zone

The area where waves break and move towards the shore in a surf-like manner, extending from the inner breaker zone to the shore.

(11) Swash zone

The innermost part of the nearshore zone, where the beach face is alternately covered by uprush (wave run-up) and exposed by backwash (wave run-down).

(12) Ocean wave

A surface wave on the ocean caused by wind, including wind waves and swells.

(13) Tide

The periodic rise and fall of sea level caused by gravitational forces exerted by celestial bodies such as the moon and the sun.

(14) Tidal current

The periodic horizontal movement of seawater caused by the gravitational pull of celestial bodies such as the moon and the sun.

(15) Storm surge

An abnormal rise or fall in sea level caused by intense winds and rapid changes in atmospheric pressure during storms such as tropical cyclones and extratropical weather systems.

(16) Sediment transport rate

The sediment transport rate refers to the amount of sediment passing through a unit width cross-section in a unit of time. Sediment transport perpendicular to the coastline is called cross-shore transport, while transport parallel to the coastline is called longshore transport.

(17) Beach restoration

The process of restoring damaged or eroded beaches to recover their coastal hazard prevention function, ecological significance, and tourism value using engineering techniques such as beach nourishment.

(18) Beach nourishment

The artificial placement of compatible sediments from other locations onto a designated coastal area to increase the width of the beach beyond the mean high tide mark, thereby restoring beach functionality. This procedure may be reinforced with particular coastal structures if necessary.

(19) Borrow area

Offshore or nearshore areas designated for sediment extraction. When designing a beach nourishment project, it is essential to identify one or more borrow areas containing sediment that meet the necessary quality standards..

(20) Sand-mud transition boundary

The boundary where beach sediments transition from sand to mud.

(21) Sediment compatibility

The degree of similarity between nourishment sand and natural beach sand, referring to the relative particle size characteristics.

(22) Nourishment volume density

The amount of nourishment sand per unit length of beach.

(23) Depth of closure

The seaward limit of effective seasonal changes on a beach profile, beyond which there are usually no significant changes in the seabed, and no notable sediment exchange between nearshore and offshore areas.

(24) Equilibrium beach profile

An ideal beach profile where erosion and deposition are in a state of relative balance under wave action.

(25) Erosion hot spot

An area that is eroding faster than the surrounding sections of the coastline or is eroding more rapidly than predicted based on sediment transport mechanisms.

3.Restoration Principles

The restoration of sandy coastal ecosystems for hazard mitigation should follow the principles outlined below.

Problem-Oriented and Context-Specific. Restoration efforts should accurately identify the hazard mitigation functions and ecological issues of sandy coasts and analyse the reasons for the decline in hazard mitigation capacity and ecosystem degradation. Considering the hazard mitigation requirements, ecological status, and natural endowments, a thorough assessment of factors, including technology, timeframe, budget, and ecological consequences, should be conducted. By developing targeted and categorized strategies, it is possible to strategically plan ecological restoration projects for hazard mitigation.

Natural Recovery as Primary, Artificial Restoration as Supplementary. The inherent mechanisms and succession laws of natural ecosystems should be promoted to preserve ecosystem diversity and connectivity. Nature should be shown respect and protected, and restoration efforts should be aligned with it. The self-repairing capacity of sandy coastal ecosystems should be improved, and human intervention should be reduced. In cases where natural recovery is not viable, existing natural conditions should be utilized, and suitable artificial supplementary measures should be implemented to facilitate the restoration of sandy coastal ecosystems and improve coastal resilience.

Land-Sea Coordination and Systematic Restoration. Restoration efforts should follow the principle of ecosystem-based considerations, addressing the functions of sandy coastal ecosystems from an integrated land–sea perspective. Systematic restoration should be conducted from the standpoint of ecosystem integrity to avoid fragmentation and damage to coastal ecosystems. The systematic spatial nature and temporal continuity of ecological restoration activities should be considered, restoration work should be carried out in steps and phases, and comprehensive supervision, ecological environment tracking, monitoring, and adaptive management should be conducted.

Reasonable, Feasible, and Risk Controllable. Restoration projects should comply with national and regional regulations for sea, island, and land use. The technical measures for sandy coasts restoration and hazard mitigation should be feasible, and the investment costs should be reasonable. Additionally, it is essential to thoroughly assess the reciprocal effects of ecological restoration activities on the surrounding areas and to avoid implementing technical measures that may have unpredictable and potentially negative impacts on both the restoration site and its vicinity.

4.Overall Technical Process

Restoring sandy coasts for marine hazard mitigation is a highly complex and comprehensive process. This requires not only consideration of the natural coastal environmental conditions but also a thorough assessment of the economic environment, development level, urban planning, and biological habitats within the restoration area, as well as social, cultural, and ecological factors.

Before implementing sandy coastal restoration projects, it is essential to collect and organize relevant comprehensive data and information. On-site inspections and background investigations should be conducted to fully understand the historical evolution and current status of the restoration area. The existing coastal issues should be analysed and diagnosed, and suitability assessments should be conducted for restoration. Based on these assessments, a beach restoration plan can then be designed.

During the project implementation, it is advisable to strengthen quality control. After the completion and acceptance of the project, follow-up monitoring, evaluation of the restoration effects, and scientific management and maintenance should be conducted.

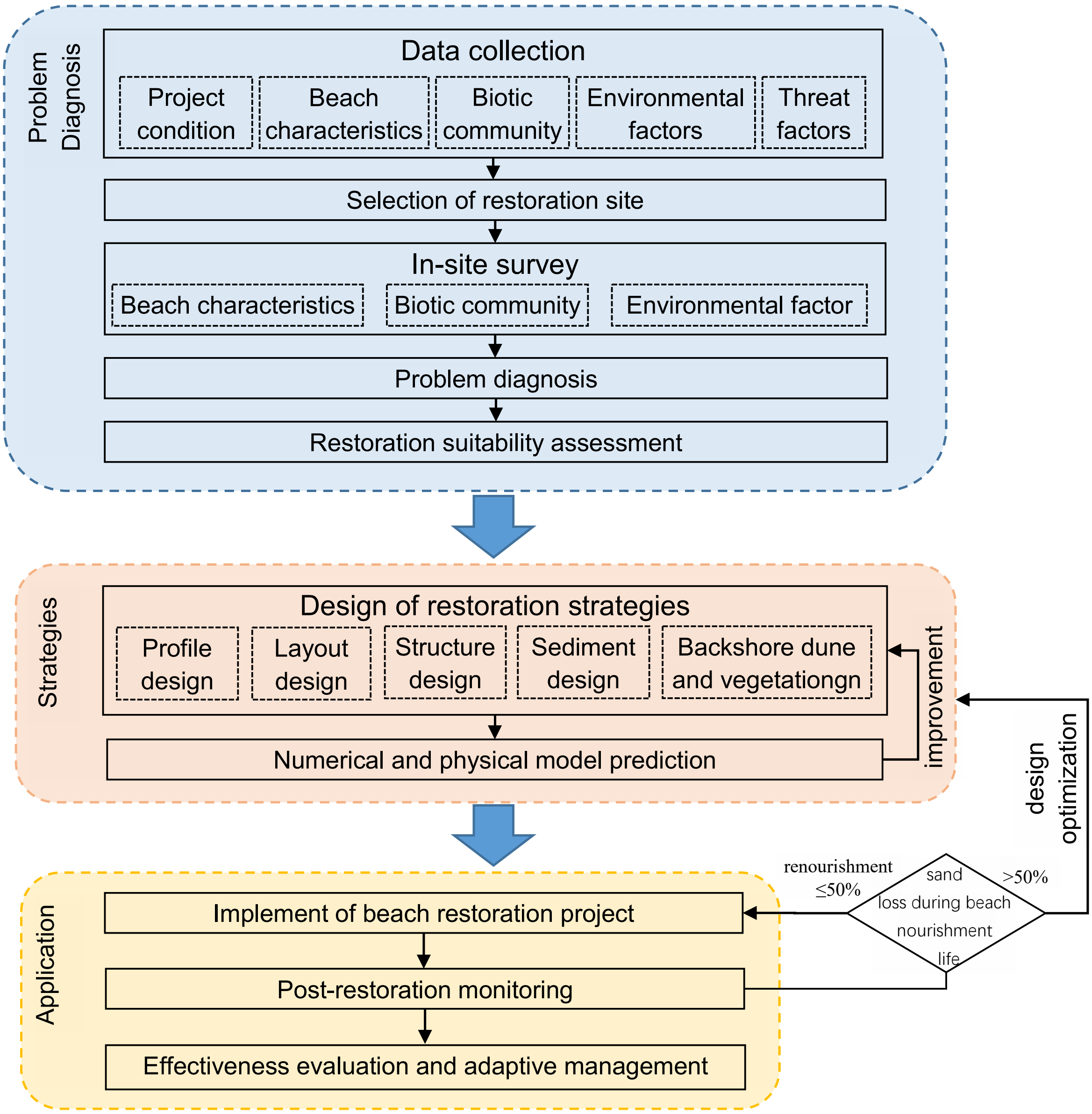


Figure 1. Workflow of Sandy Coast Restoration for Marine Hazard Mitigation

5.Baseline Survey

5.1 Objectives

The objective of the current status survey of sandy coasts is to gain insight into the environmental components of the beach and adjacent coastal zones, encompassing the geomorphology, dynamics, water quality, and biological factors. This dataset serves as a basis for evaluating the erosion and accretion states of sandy coasts and for devising restoration strategies. Furthermore, exploring sandy coasts with varying evolutionary stages, diverse profiles and layout features can aid in the formulation of tailored restoration schemes and can offer practical frameworks for restoration initiatives.

5.2 Content and Methods

(1) Historical Evolution of Sandy Coasts

Planning and selecting suitable areas for restoration requires a thorough assessment of the current characteristics of sandy coasts. By examining the evolution process of sandy coasts, we can gain insights into the factors and processes that have shaped the current coastal conditions, which can serve as a valuable reference for designing artificial beaches. In cases where damaged sandy coasts require beach nourishment, it is crucial to have a comprehensive understanding of the evolution process of beach landforms, including changes in the coastline and in dry beach areas. This necessitates analysing the factors contributing to beach landform damage, assessing the level of coastal damage, determining the background erosion rate, and proposing tailored restoration strategies to recover the original healthy beach landforms.

The factors influencing the changes in sandy coasts are complex and varied.

Fundamentally, coastal landform changes result from the migration of coastal sediments under dynamic forces. Any factor that causes changes in sediment or nearshore hydrodynamics can lead to coastal landform changes. The main direct and indirect factors affecting sandy coastal landform changes are shown in Table 1.

Table 1. Major Factors Influencing Sandy Coastal Landform Changes

	Long-term (years to centuries)	Short-term (days to years)
Direct Influence	Decrease in coastal sediment volume due to weathering, dissolution, abrasion, and compaction	Sand mining from beaches and nearshore areas Sediment transport by waves and currents
		Aeolian sediment transport
		Drainage-induced sediment transport (e.g., culverts)
		Beach tourism activities
Indirect Influence	Global climate change	Offshore sand mining
	Sea level rise	Storm surge
	Decreased sediment input from rivers into the ocean	Construction of upstream seawalls, groynes, and breakwaters
	Soil and water conservation in watersheds	Decreased sediment supply from coastal dunes
	Diversion of river course	Construction of backshore revetments
	Decreased sediment supply from cliff erosion	Changes in beach groundwater levels
	Decreased sediment supply from offshore	Construction of buildings on the beach
	Offshore sandbar migration, coral reef damage	

(2) Coastal Dynamics

Coastal dynamic environment surveys encompass a variety of factors, including waves, currents, suspended sediment, tidal levels, winds, and long-term sea level fluctuations. Table 2 outlines the key criteria for each dynamic survey project.

The wave survey is conducted to determine the wave conditions within the sandy coast restoration area and to provide dynamic data to support predictions of the evolution of beach restoration projects. It is necessary to collect continuously measured data for at least one year within the past five years. Observation sites should be situated in open sea areas devoid of obstacles such as islands, reefs, sandbars, and fishing zones and should preferably avoid steep shores. The depth at the location where the buoy or sensor is deployed should generally be no less than 10 metres, with a level seabed, and should be away from areas with strong currents. Upon deployment of the sensor or wave buoy, immediate measurements and recordings should be taken of the water depth, tidal height during deployment, geographical coordinates, horizontal distance from the onshore observation site, and deployment time.

Nearshore currents are primarily influenced by tidal currents and wind-driven currents. Under specific conditions, other coastal currents, such as longshore currents and rip currents resulting from wave breaking, can also play a significant role. These currents play a crucial role in sediment transport, geomorphological evolution, and the stability of restoration projects. The selection of the current observation area should be based on project requirements, local hydrometeorological conditions, and topographical features, with a focus on the proposed project area and its surroundings. The key parameters to observe are the current speed and direction, with supplementary parameters including the wind speed and direction. Observations should be carried out at least once each in winter and summer. Continuous current observations should last for a minimum of 25 hours, with a frequency of at least one observation per hour. The observation layers are determined by water depth: for water depths of $H \geqslant 5.0$ m, six layers should be observed (surface, 0.2H layer, 0.4H layer, 0.6H layer, 0.8H layer, and bottom layer). For water depths of $3.0 \leqslant H<5.0$ m, three layers should be observed (0.2H layer, 0.6H layer, and 0.8H layer). For water depths of $1.5 \leqslant H<3.0$ m, two layers should be observed (0.2H layer and 0.8H layer). For water depths of $H<1.5$ m, one layer should be observed (0.6H layer).

The objective of the suspended sediment survey in the project area is to investigate sediment transport pathways and fluxes and to elucidate the influence of sediment transport on coastal erosion and deposition patterns. This survey provides a basis for the construction of sandy coast restoration projects. The suspended sediment monitoring in the project area should be carried out concurrently with the current monitoring efforts, utilizing the same monitoring layers and frequency. In the case of straight coastlines, hydrological cross-sections should be positioned perpendicular to the coastline. However, for curved coastlines or those with estuaries, the number of sections should be adjusted accordingly based on specific conditions.

A tidal level survey primarily involves the measurement of tidal heights at various times, particularly during high and low tides. Observation points should be selected in areas that are open to the sea, with relatively calm water flow, minimal sedimentation, and weak wave impact. Locations with significant erosion or unstable coastlines should be avoided. The water depth at the theoretical lowest tide should exceed 1 m. It is recommended to utilize existing maritime structures such as breakwaters, piers, and jetties. When installing sensors underwater, their height should be at least 1 m below the reference tidal height. The observation station should establish a primary benchmark and one or two check benchmarks in suitable positions. The primary benchmark serves as a permanent elevation control point for the observation station, while the check benchmarks are used to calibrate and confirm the zero point and reading height of the tide gauge.

Nearshore wind conditions not only impact wave characteristics but also play a crucial role in the transport of wind-blown sand, making it a significant consideration in sandy coastal restoration projects. It is essential to gather wind speed data for a minimum of one year in close proximity to the project site during the restoration process. The wind condition assessment should encompass the following parameters: instantaneous wind speed and direction, daily maximum wind speed and direction, daily extreme wind speed and direction, and duration of wind speeds equal to or exceeding 17.0 m/s. The observation site should be situated in a flat and unobstructed area to avoid local topographic changes and obstacles that could disrupt airflow. The recommended size for the observation site is typically 25×25 m, although adjustments may be necessary on islands or platforms due to spatial constraints. Sensors should be positioned on the north side of the observation site at a height of 10-12 m above ground level; if mounted on a platform, they should be placed 6-8 m above the platform surface and no less than 10 m above the ground.

Regional sea surface changes occur at a relatively slow pace; however, the long-term effects of sea level rise on coastal geomorphology are significant and cannot be disregarded. It is typically necessary to gather data on sea level changes over the past 30 years in the project area to assess the impact of these changes on restoration projects.

Table 2. Contents and Requirements for Coastal Dynamic Survey

Item	Requirements
Waves	Observation Period: Collect or observe at least 1 year of continuous measured data within the last 5 years. Station Layout: Stations should be placed in the sea area near the restoration area at a water depth of 10-15 metres. Observation Technology Requirements: Follow the "Coastal Observation Specification" GB/T 14914-2006.
Currents	Observation Period: Conduct observations at least once in winter and once in summer, with a continuous observation time of no less than 25 hours. Area Layout: Near the project area, generally located in the central part of the project area. Observation Technology Requirements: Follow the "Ocean Survey Specification" GB/T 12763.2-2007.
Suspended Sediments	Observation Period: Conduct observations at least once in winter and once in summer, with each observation lasting no less than 25 hours continuously. Station Layout: Vertical layout along the coastline, with no less than 2 stations. Observation Technology Requirements: Follow the "Harbor Hydrology Specification" JTS145-2-2013.
Tidal Level	Observation Period: Collect or observe at least 1 year of continuous measured data within the last 5 years, ideally synchronized with wave observations. Observation Technology Requirements: Follow the "Ocean Survey Specification" GB/T 12763.2-2007.
Wind	Observation Period: Collect or observe at least 1 year of continuous measured data within the last 5 years, ideally synchronized with wave observations. Station Layout: In the open area of the coastal restoration area. Observation Technology Requirements: Follow the "Coastal Observation Specification" GB/T 14914-2006.
Regional Sea Level	Collect data on regional sea level changes in recent years (not less than 30 years).

(3) Sediments

The investigation of sediments includes surveys of beach sediments, subaqueous sediments, and beach sediment drilling. Sediment surveys help to understand the sediment characteristics of the engineering coastal environment and provide a basis for selecting the grain size for replenishment sand during sandy beach restoration. The basic content and requirements of the sediment surveys are shown in Table 3. Sampling of beach sediments and subaqueous sediments should ideally be synchronized with topographic surveys, ensuring that sampling sites are consistent or close in different periods. Beach sediment drilling surveys are conducted to explore the sand source reserves, sediment characteristics of sandy beaches, and records of extreme dynamic events, providing a reference basis for the design of sandy beach restoration in sandy coastal areas.

Figure 2. Collection of Surface Sediments and Core Samples from Beaches

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

Table 3. Contents and Basic Requirements for Sediment Surveys

Item	Requirements
Monitoring of Beach Sediment Grain Size Variation	Location: Sampling profiles should match monitoring profiles, including representative locations such as beach shoulders, high tide zones, mid-tide zones, low tide zones, etc., and sampling points can be increased based on site characteristics. Depth: Surface to 20 cm. Timing: Ideally synchronized with beach measurements.
Monitoring of Seabed Sediment Grain Size Variation	Sampling Density: Sampling density increases gradually from sea to land in the project area, with no less than 10 samples per square kilometer. Depth: Surface. Frequency: Not less than twice a year, once in winter and once in summer.

Item	Requirements
Beach Sediment Drilling Survey	Use excavation trenches or drilling methods to investigate beach sediment characteristics. Location: Should include representative locations such as beach shoulders, high tide zones, mid-tide zones, low tide zones, etc., and drilling points or trenches can be increased based on site characteristics.

(4) Topography

The topography survey mainly includes nearshore terrain, beach profile, and shoreline change monitoring, the content and requirements of which are shown in Table 4.

beach topographical survey

Nearshore terrain measurements can provide basic data for calculating wave fields, predicting beach evolution, and determining the amount of beach replenishment in the design of sandy beach restoration. It is necessary to first understand historical depth measurement data and the latest published submarine topographic maps and nautical charts. The scale of underwater terrain measurements should generally not be less than 1:5000, and the scale of beach terrain measurements should generally not be less than 1:1000. During depth measurement, the accuracy of navigation positioning should be better than 10 metres. When the water depth is less than 30 m, the accuracy of the depth measurement should be better than 0.3 m; when the water depth is greater than 30 m, the accuracy of the depth measurement should be better than 1% of the water depth.

Beach profile monitoring can provide data support for the analysis of changes in beach erosion and accretion. The number of profiles is determined according to the size of the project area, generally requiring no less than 5 profiles per kilometer. In special cases, the number of profiles may increase based on changes in coastal morphology. Periodic observations should be conducted at least once a quarter, and additional measurements should be taken after typhoon events.

Shoreline change monitoring should be initiated one year before the design of sandy beach restoration projects. The monitoring range should include the shoreline of the project area and its surrounding coastal units. Measurements should be taken at least once in winter and once in summer and ideally synchronized with the winter and summer measurements of beach profiles. Additional measurements should be taken after storm surge events to determine the trend of shoreline changes.

Table 4. Contents and Basic Requirements for Topography Survey

Item	Requirements
Nearshore Topography Measurement	Range: The coastline of the proposed restoration area extends to the 10 m isobath. Measurement Scale: Underwater topography not less than 1:5000; beach topography generally 1:1000. Measurement Techniques: Follow the "Specifications for Oceanographic Surveys" GB/T 12763.2-2007.
Beach Profile Topography Monitoring	Range: From the backshore of the restoration area to the sea to an average minimum tidal depth of 0.5 m. Section Layout: Sections are vertically laid out along the water's edge, with a density of no less than 5 per kilometer, and the base point is fixed. Measurement Frequency: At least once a year, not less than once a quarter, with additional measurements after typhoon events. Measurement Techniques: According to the "Specification for Marine Engineering Topographic Survey" GB17501-2017.
Shoreline Change Monitoring	Range: The coastal unit where the restoration area is located and its nearby coastline. Measurement Frequency: At least once a year, with measurements in winter and summer, and additional measurements after typhoon events. Measurement Techniques: According to the "Specification for Marine Engineering Topographic Survey" GB17501-2017. Collect historical shoreline comparison data to understand past shoreline change characteristics.

(5) Backshore Vegetation

Backshore vegetation is an important biological type on sandy coasts. It serves as a biological buffer zone for wave dissipation, energy dissipation, and hazard mitigation on sandy coasts. It is also an important index for evaluating the ecological and hazard mitigation benefits of sandy coast restoration. The purpose of backshore vegetation investigation is to understand the types, distribution, and community

quadrat survey of backshore vegetation

structure of sand-dwelling vegetation on sandy coasts in order to carry out targeted plant selection, soil improvement, and plant configuration for backshore sandy land vegetation restoration design. The basic survey elements and requirements are shown in Table 5.

Table 5. Contents and Requirements for Backshore Vegetation Investigation

Survey Elements	Vegetation type, plant species, area, number of plants, height, diameter at breast height, crown width, coverage, and vitality.
Site Setup	a) Transect setup: Survey transects should be distributed in representative sections throughout the survey area, avoiding any gaps, and the routes should be recorded using GPS. b) Quadrat setup: The main quadrat is usually set as a square, with an area of 100 m^2 for trees, 25 m^2 for shrubs, and 1 m^2 for herbaceous plants. The distance between two plots should be no less than 100 m, with at least one plot for each plant community.
Survey Frequency	a) Regular survey: Conducted once a year, preferably between May and September. b) Storm period survey: Conducted once within one month after a storm.
Technical Requirements	a) For trees and small trees with a diameter at breast height (DBH) ⩾ 5 cm, each tree should be measured. Shrubs and herbaceous plants should be surveyed and recorded as clumps or individuals, and a plant resource record form should be completed. b) The interpretation of satellite remote sensing images with a resolution of no less than 0.6 m can be used to obtain the area of backshore vegetation. The interpretation of drone remote sensing images with a resolution of no less than 0.3 m can be used to obtain the area of backshore vegetation.

(6) Benthic Organisms


beach benthic Organisms survey

With increasing concern for marine environmental quality, changes in benthic organisms under the influence of sandy beach restoration projects are receiving increasing attention. They are also becoming one of the indicators for assessing the effectiveness of restoration projects. The purpose of benthic organism surveys is to understand the species composition and distribution of underwater benthic organisms. Such surveys aim to make reliable estimates of the average density and biomass of benthic organisms per unit area. These survey data can be used to assess the degree of pollution in beach environments and water bodies. The basic survey elements and requirements are shown in Table 6.

Table 6. Contents and Requirements for Benthic Organism Surveys

Survey Elements	Species composition of benthic animals and plants, quantity (habitat density, biomass, or existing quantity), horizontal distribution, and vertical distribution.
Survey Density	Typically, 2 stations in the high tide zone, 3 stations in the mid-tide zone, and 1 or 2 stations in the low tide zone. For narrow intertidal zones, 1 station in the high tide zone, 3 stations in the mid-tide zone, and 1 station in the low tide zone.
Survey Cycle	Conduct surveys in spring, summer, autumn, and winter, covering all four seasons; Alternatively, conduct surveys in spring and autumn.
Survey Timing	Intertidal biological sampling must be conducted during spring tides; Alternatively, sample the low tide zone during spring tides and sample the high and mid-tide zones during neap tides.
Technical Requirements	For hard substrate (rocky shore) biological sampling, use a 25 cm×25 cm quadrat to sample 2 quadrats; For areas with dense biological populations, use a 10 cm×10 cm quadrat for sampling; For soft substrate (mudflats, sandy mudflats, beaches) biological sampling, use a 25 cm×25 cm×30 cm quadrat to sample 4 to 8 quadrats. Conduct qualitative sampling and observation simultaneously, with at least 1 sample taken from each of the following: the high tide zone, mid-tide zone, and low tide zone.

(7) Water Quality

Seawater environmental quality monitoring can be used to further understand the basic status of seawater chemistry near coasts, to accumulate basic data on seawater chemistry, to improve the comprehensive understanding of the distribution and variation of seawater environments under the influence of sandy coastal restoration projects, and to provide background information and a decision-making basis for sandy coastal restoration, coastal zone protection, and management. The basic indicators and requirements for seawater environmental quality monitoring are shown in Table 7.

Table 7. Basic Indicators and Requirements for Seawater Quality Monitoring

Monitoring Indicators	Water quality monitoring elements include fecal coliform, transparency, salinity, suspended solids, oils, pH, and dissolved oxygen. Relevant items can be added appropriately according to the site characteristics. Hydro-meteorological elements include: water temperature, wind direction, wind speed, precipitation, air temperature, and visibility.
Monitoring Range	The water area extends 3 km on both sides along the main flow direction of the project area. The monitoring stations are evenly distributed throughout the water area, including points with the greatest impact during construction and peripheral points susceptible to external pollution.
Monitoring Frequency	Monitoring is better to be scheduled in June to September (peak swimming season) and December to February (off-peak swimming season). Monitoring during both spring and neap tides is required for each period.
Monitoring Levels	For depths <5 m, collect surface water; for depths ⩾ 5 m and <10 m, collect bottom water; for depths ⩾ 10 m, collect mid-bottom water (surface is 0.1-1 m below the sea surface, and bottom is 2 m above the seabed).
Emergency Monitoring	Emergency monitoring of seawater environmental quality is required in the following situations: ① When a significant deterioration trend in water quality is detected, relevant parameters should be monitored. ② When water-related epidemics occur locally, microbial quantity monitoring should be intensified. Different microbial parameters such as Salmonella, enterococcus, and pathogens should be monitored according to the type of epidemic. ③ In the event of emergencies in nearby waters, such as oil spills or red tides, targeted monitoring is also needed.
Technical Requirements	In accordance with the "Specifications for Marine Surveys" (GB12763-2007) and the "Specifications for Marine Monitoring" (GB17378-2007).

6.Problem Diagnosis and Suitability Assessment for Restoration

6.1 Problem Diagnosis

Based on the current status survey of sandy coasts, analyze and diagnose the existing problems along the coast. The identification of problems associated with the ecological restoration of sandy coasts mainly includes the assessment of beach erosion, beach quality, coastal hazard mitigation function, and ecological degradation.

Diagnosis of beach erosion: Evaluators should determine the equilibrium state and conditions of the beach through investigation and analysis, identify the key causes of beach erosion, quantify the degree of erosion, and assess the impact of beach damage on marine resources, the environment, and public life and production activities.

Diagnosis of beach quality: This includes the assessment of natural and development quality. Based on collected data and background field investigations, a comprehensive evaluation of beach quality is conducted, and the repaired beaches are classified. The evaluation of the natural quality, development quality, and comprehensive quality of beaches should be carried out in accordance with "Beach Quality Evaluation and Grading" HY/T 254—2018.

Diagnosis of coastal hazard mitigation function: This includes a comprehensive assessment of the wave dissipation capacity of sandy coasts, as well as the hazard mitigation buffering capacity and postdisaster self-recovery ability. The evaluation of the wave dissipation capacity should be conducted in accordance with Part 7 of the "Technical guideline on coastal ecological rehabilitation for hazard mitigation" T/CAOE 21.7-2020, and the evaluation of the hazard mitigation buffering capacity should be conducted in accordance with Part 8 of the "Technical guideline for investigation and assessment of coastal ecosystem" T/CAOE 20.8-2020. The postdisaster self-recovery ability can be assessed based on monitoring and mathematical models.

Diagnosis of ecological degradation: This procedure should include the factors, degree, and reasons for the degradation of intertidal biological communities and backshore vegetation communities. The indicators and methods for ecological degradation diagnosis should be in accordance with Sections 6.5.2 and 6.5.3 of the "Guidelines for Marine Ecological Restoration Technologies—Part 1: General Principles" GB/T 41339.1—2022.

6.2 Suitability Assessment for Restoration

Based on the results of the problem diagnosis, a suitability assessment can be conducted for the ecological restoration of sandy coasts. The evaluation and analysis mainly include the following:

Analysis of beach damage mechanisms: This includes analyses of beach damage, sediment transport status, human activities in the surrounding area, coastal sediment transport, the impact of structures on the beach, and the causes of erosion hotspots.

Analysis of policy and planning suitability. The site selection for sandy coast restoration should adhere to, but not be limited to, the following planning requirements: marine functional zoning, marine use planning, territorial spatial planning, and urban construction planning.

Analysis of coastal dynamic suitability: Field investigations and numerical simulations are used to analyse the dynamics of nearshore waves and extreme storms in the restoration area. The influences of water depth, topography, coastline morphology, and structure on wave dynamics are evaluated. The potential areas of erosion hotspots and the possibility of beach mudification are analysed.

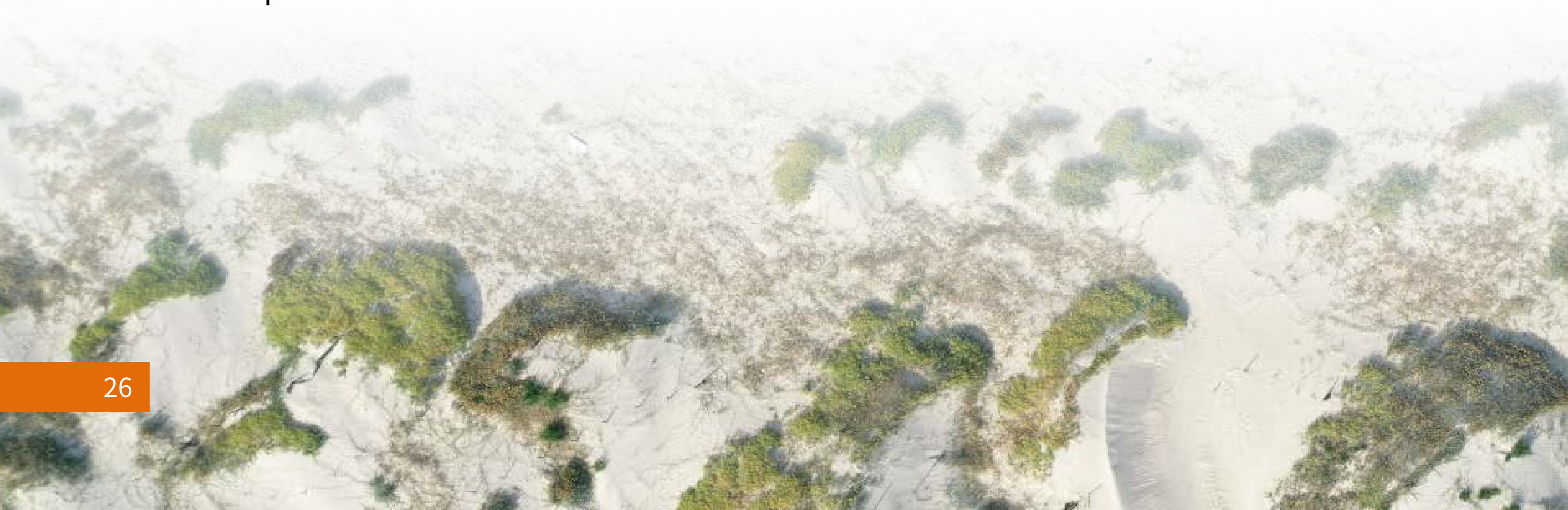
Analysis of coastal geomorphological suitability: This includes determining whether the terrain and geomorphology of the project area are suitable for the formation of beaches, either naturally or through artificial structures. It also considers the wave dissipation and buffering capacity of the existing beach geomorphology against storm surges.

Analysis of coastal water and sediment quality suitability: This analysis evaluates whether the nearshore water quality and sediment characteristics meet the requirements for sandy coast restoration. These efforts should comply with the provisions of HY/T 255—2018 sections 4.4 and 7.5. The potential ecological impacts of beach nourishment construction and subsequent beach evolution, should also be assessed.

7.Restoration Goals

Based on the results of the problem diagnosis and suitability assessment for remediation, the ecological restoration goals for sandy coasts can be determined. The restoration goals should not only focus on restoring shoreline morphology but also consider ecological protection, hazard prevention and mitigation, and social factors such as coastal tourism. Therefore, coastal restoration goals need to be carefully formulated.

From a safety perspective, the goal of sandy coast restoration is to rapidly restore the eroded natural shoreline morphology through beach nourishment, thereby widening the flexible buffer zone of the coastal area to better withstand marine hydrodynamics and effectively enhance the capacity of sandy coast to resist marine disasters such as typhoons and storms. From an ecological standpoint, the objective of sandy coast restoration is to create favorable habitat conditions for flora and fauna through the integration of beach restoration and the rehabilitation of backshore vegetation, ultimately establishing a healthy coastal ecosystem. From an economic perspective, the aim of sandy coast restoration is to expand public access to recreational waterfront spaces following beach nourishment, thereby boosting beach tourism revenue, increasing the value of properties in the coastal hinterland, and promoting rapid development of the coastal economy. By integrating the above safety, ecological, and economic objectives, a healthy living shoreline system incorporating "hazard mitigation capacity, ecosystem vitality, and economic development potential" can be achieved, thereby supporting high-quality development of coastal economies.



8.Restoration Methods

What are the restoration methods for sandy coasts?

For restoring damaged sandy coastlines, it is necessary to first analyze the causes of damage, understand the extent and development of the damage, and assess the background erosion rate of the coastline. Corresponding restoration measures should be developed based on different direct erosion causes.

For sandy coastlines that require maintenance, the existing beach conditions (including length, width, slope, grain size, etc.) are often inadequate to meet the needs of hazard prevention and mitigation, urban planning, and development demands. Therefore, beach maintenance is needed to improve beach quality, enhance hazard prevention capabilities, increase beach capacity, and enhance the attractiveness of tourist beaches. For such artificial beach projects, it is important to consider beach evolution under maintenance conditions, such as beach widening, lengthening, or changes in sediment grain size. Predictions should be made regarding the retreat rate, erosion hotspots, profile changes, and hazard mitigation functions of the maintained beaches

For the segments of coastlines where original beaches have been lost due to human activities, considerations of urban health, sustainable development, and people's desire for a better living environment are important. If there are plans to recreate sandy beaches, it is necessary to first analyse the feasibility of beach redevelopment. Classic beach development theories can be used to study whether the nearshore environment still possesses the dynamic factors and sediment characteristics necessary for beach development or maintenance. This can be verified using physical and numerical models. Additionally, the method of regional analogy can be used to infer suitability based on adjacent segments and similar environmental conditions.

9.Restoration Measures

9.1 Profile Design for Sandy Coast Restoration

9.1.1 Profile Types

Previous research indicates that finer sand used for nourishment creates a gentler equilibrium profile slope, while coarser sand results in a steeper slope. The coarser the grain size is, the greater the dry beach width (Δy_0) per unit sand volume.

Sandy coast restoration profiles can be categorized into "intersecting", "non-intersecting", and "submerged" profiles based on grain size. For an intersecting profile (Figure 3a), a necessary but not sufficient condition is that the nourishment sand should be coarser than the natural sand. The advantage of this profile is that the nourished profile intersects with the natural profile, meaning that it does not need to extend to the closure depth $h*$.

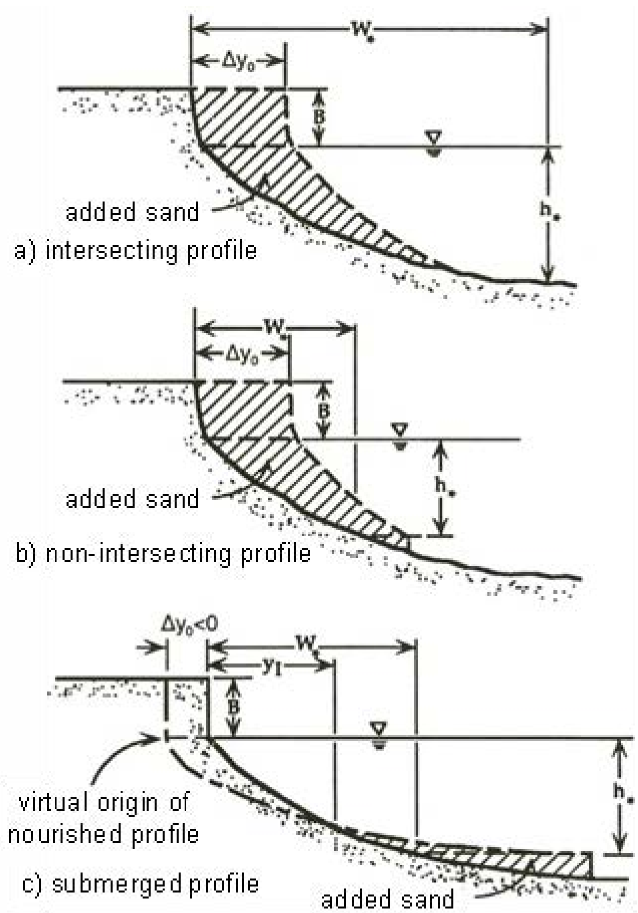


Figure 3. Three generic types of nourished profiles. Cited from Dean[1] (Source: Dean, 1991)

A non-intersecting profile (Figure 3b) is commonly observed in most beach nourishment projects. This profile appears when the grain size of the nourishment sand is similar to or slightly finer (or sometimes coarser) than that of the natural sand. This profile type extends to the closure depth $h*$. The third type is the submerged profile (Figure 3c), which does not extend landward to the shoreline and thus does not increase the dry beach width. This type of profile is also observed in the non-intersecting category and requires the nourishment sand to be finer than the natural sand.

9.1.2 Profile Design Approaches

There are various methods for designing the beach profile morphology of sandy coasts. Many studies have shown that using a single method for profile design may not achieve optimal results. Instead, multiple design methods for determining the beach profile morphology and the range of sand nourishment volumes per unit width should be compared and verified. This handbook lists three commonly used methods for designing beach profiles on sandy coasts.

(1) Dean's Equilibrium Profile Model

Bruun[2] initially proposed that the beach profile satisfies the expression $h=Ax$. Dean[1,3] later theorized this model and derived the beach equilibrium profile model:

$$h=Ax^m$$

where h is the local water depth (m), x is the offshore distance (m), m is a statistically obtained coefficient, and A is related to the settling velocity w, given by A=0.067$w^{0.44}$ (where w=14D$^{1.1}$ and D is the mean grain size).

Dean fitted this model to 504 beach profile datasets from the Atlantic coast of the USA and the Gulf coast of Mexico and found that the value of m ranged between 0.2 and 1.2, following a normal distribution with an expected value of 2/3. Thus, 2/3 is generally used as the value for m. Dean's model is simple and practical, and it has been widely applied in designing the profiles of sandy coast beach restoration projects in the United States.

(2) Dutch Empirical Method

In 1992, Verhagen proposed an empirical method for beach nourishment widely used in the Netherlands. This method primarily consists of five steps, some of which may not be applicable to certain specific projects [4]: 1) conduct at least 10 years of shoreline measurements in the project area to provide background erosion rates; 2) use at least 10 years of measurement data to calculate the annual sand loss for the shoreline segment; 3) add 40% to the calculated sand loss to account for additional losses; 4) multiply the resulting value by an appropriate "half-life," such as 5 years; and 5) replace the calculated quantity of sand on the beach between the low tide line and the dune base to complete the beach nourishment project. One drawback of this method is that after the selected "half-life" period, background erosion, which is the main cause of sediment loss, will erode all the placed sand. The additional 40% sand is considered to compensate for the longitudinal diffusion losses of the sand from the nourishment project (Figure 4a). The amount of sand required for subsequent beach nourishment projects can be determined based on the results of previous nourishment projects. The Dutch empirical method is simple and straightforward, and it assumes that placing any high-quality sand on the beach will benefit the shoreline.

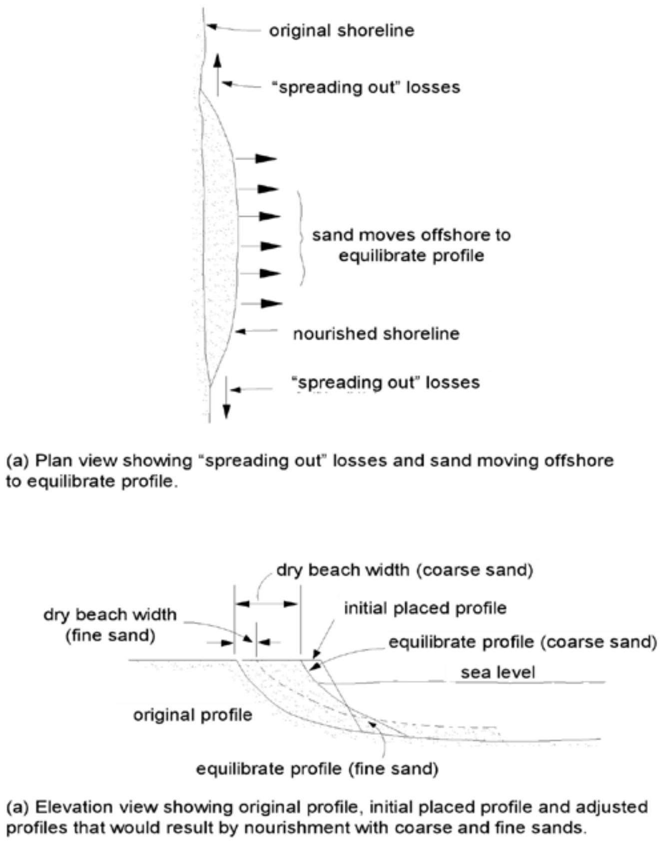


Figure 4. Sediment transport and losses related to beach nourishment projects[5]

(Source: Dean, 2002)

(3) Profile Analogy Method

Due to the influences of regional tectonics, climate zones, dynamic conditions, and sediment supply, the morphology of sandy coasts varies significantly among different regions. In some special cases, different segments of the same coast can exhibit distinctly different beach morphologies. In the context of a macrotidal coast, Masselink and Short[6] proposed that the main beach morphodynamic types are extradissipative beaches and low-tide terrace beaches. In such a unique, high-energy tidal environment, traditional equilibrium beach theory models are often inapplicable. The actual beach profile morphology can deviate significantly from Dean's equilibrium profile model (Figure 5). Therefore, coastal engineers must fully consider the actual beach characteristics when designing sandy coast restoration profiles.

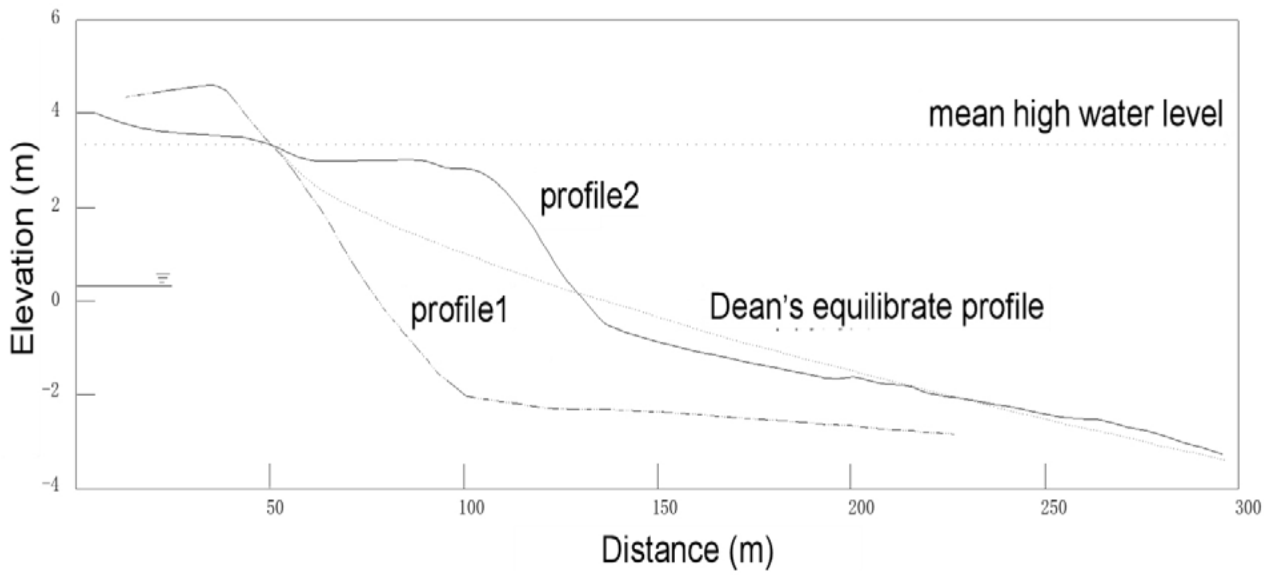


Figure 5. Comparison between Measured Beach Profile Morphology and Dean's Equilibrate Profile Model. Profiles 1 and 2 represent typical low-tide terrace beach profiles on macrotidal coasts [7] (Source: Shi et al., 2013)

When traditional beach equilibrium profile design methods are not applicable, the profile analogy method becomes a crucial alternative. This method involves comparing the target restoration coast with adjacent sandy coasts that have similar dynamic conditions and sediment characteristics. The restoration target coast might be eroded or degraded due to natural or anthropogenic factors, while the adjacent analogous coast or coastal unit remains well preserved or in a state of dynamic equilibrium. By referencing the morphology of the analogous beach, the restoration profile for the eroded coast can be designed.

The profile analogy method can serve as a guiding approach for sandy coast restoration design and can also be used to verify the feasibility and accuracy of other design methods. The application steps of the coastal profile analogy method are as follows:

A. Conduct a comprehensive analysis of the nearshore dynamic environmental conditions, coastal geomorphology types, shoreline orientations, beach profile types, and sediment characteristics of adjacent coastal segments;

B. Based on the analysis, select the sandy beach most similar to the restoration area;

C. Establish observational cross-sections at typical locations on the analogous beach (e.g., the middle, sides, or significantly changing areas) to conduct periodic beach profile measurements. The measurement range should include the area from the lowest tide line to above the mean high tide line to determine the beach profile shape;

D. Design the sandy coast restoration profile based on the profile characteristics of the analogous beach.

9.1.3 Four Typical Nourishment Profiles

The design of nourishment profiles directly determines the effectiveness of restoration. Four typical nourishment profiles include dune nourishment, berm nourishment, foreshore nourishment, and subaqueous sandbar nourishment.

(1) Dune Nourishment (Figure 6): This method involves depositing sediment on the backshore of the beach, enhancing the height and width of the backshore dunes and increasing the coast's protective level and buffering capacity against extreme dynamic events. Combined with the restoration of backshore vegetation, this method

can improve the ability of coasts to defend against wind and sand. This nourishment method is defensive in nature and is not intended to increase the dry beach width for recreational space. It is typically used in low-lying coastal areas and regions with intense wind and sand activity. The technical process of dune restoration is detailed in section 9.6.

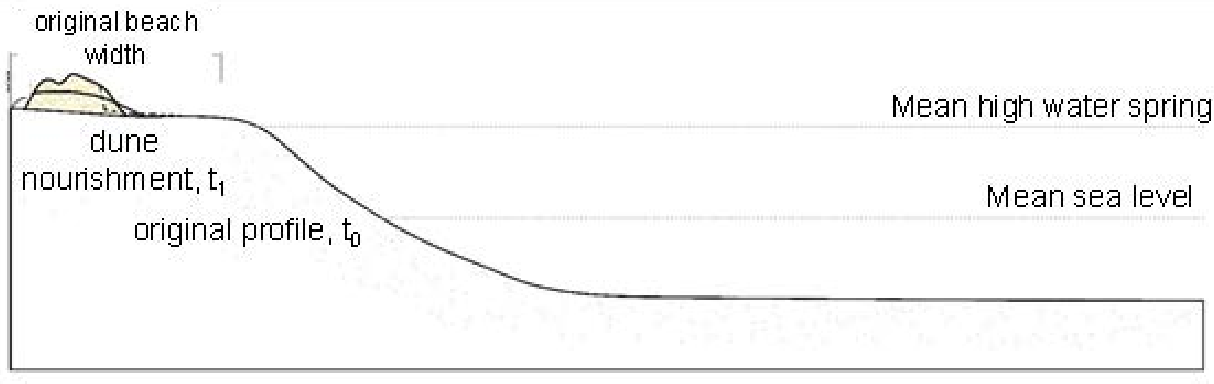


Figure 6. Typical Nourishment Profiles: Dune Nourishment [8]

(Source: Qi et al., 2021)

(2) Berm Nourishment (Figure 7): This method involves directly depositing sediment on the leading edge of the berm to quickly increase the beach space. It can directly expand the dry beach width, and postrestoration, the beach will undergo natural adjustments under dynamic forces, gradually reducing and stabilizing the dry beach width. This nourishment method is simple in construction, with rapid initial beach surface changes, requiring a longer time to form a balanced profile. Storm waves are the main driving force behind beach evolution. Berm nourishment is the most common nourishment method in China, especially for restoration projects that require rapid expansion of recreational space. The design of berm elevation should take the local historical high-water level, wave runup, landscape elevation, existing beach elevation, adjacent beach elevation and nourishment cost into consideration. A degree of overwashing is allowed under extreme weather. The berm elevation can be determined with reference to the "Technical Guide for Beach Nourishment and Restoration" (HY/Y 255-2018).

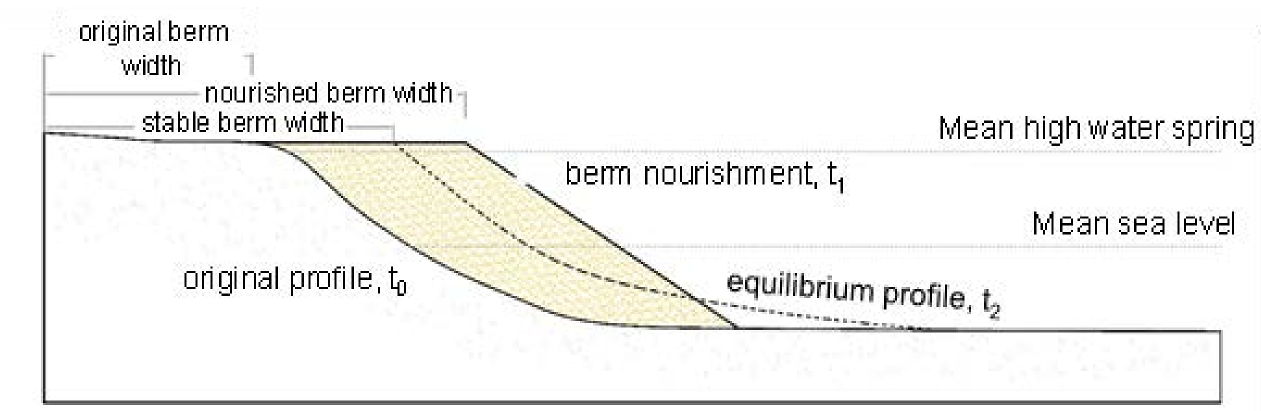


Figure 7. Typical Nourishment Profiles: Berm Nourishment[8]

(Source: Qi et al., 2021)

(3)Foreshore Nourishment (Figure 8): This method involves nourishing the entire foreshore profile and artificially shaping it into a near-equilibrium profile. This method requires precise design of the nourishment sediment grain size, profile shape, and overfill ratio. After restoration, the shoreline can reach an equilibrated state in a short period, with minimal changes to the shoreline and a relatively stable dry beach width. However, foreshore nourishment demands high technical standards, and storm impacts during the construction period can significantly affect the project.

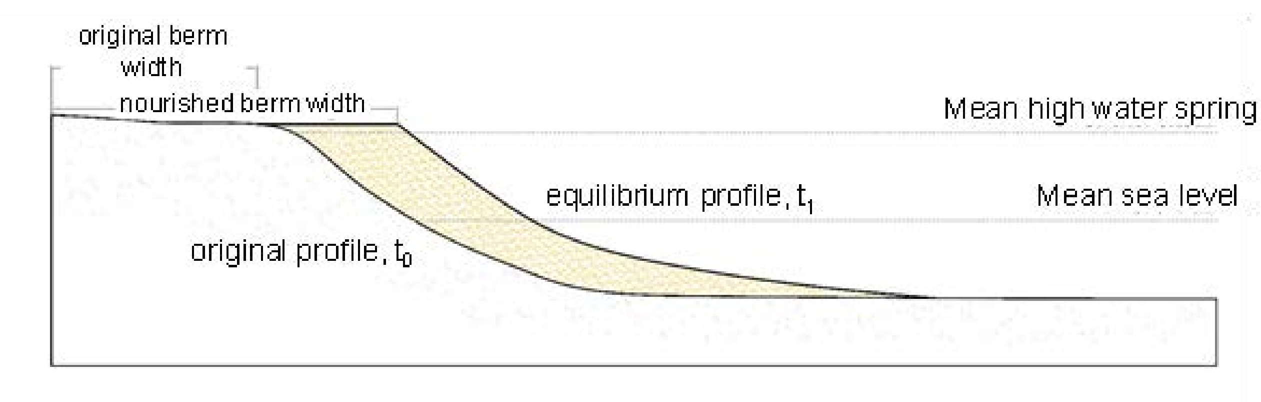


Figure 8. Typical Nourishment Profiles: Foreshore Nourishment[8]

(Source: Qi et al., 2021)

(4) Subaqueous Sandbar Nourishment (Figure 9): This method involves

depositing sediment in the nearshore underwater area to form an artificial sandbar parallel to the coast. On the one hand, it acts as a soft submerged breakwater that serves as a barrier to dissipate waves and protect the shore. On the other hand, it continuously supplies the beach through wave action, gradually increasing the beach's surface area. The depth, height, and slope of the sandbar crest are crucial factors affecting its stability and dynamic beach protection effectiveness. This nourishment method can effectively enhance the protective capability of sandy coasts but does not directly increase the width of the dry beach. It is not suitable for sandy coast restoration projects aimed at increasing recreational space and is typically used in combination with other nourishment methods.

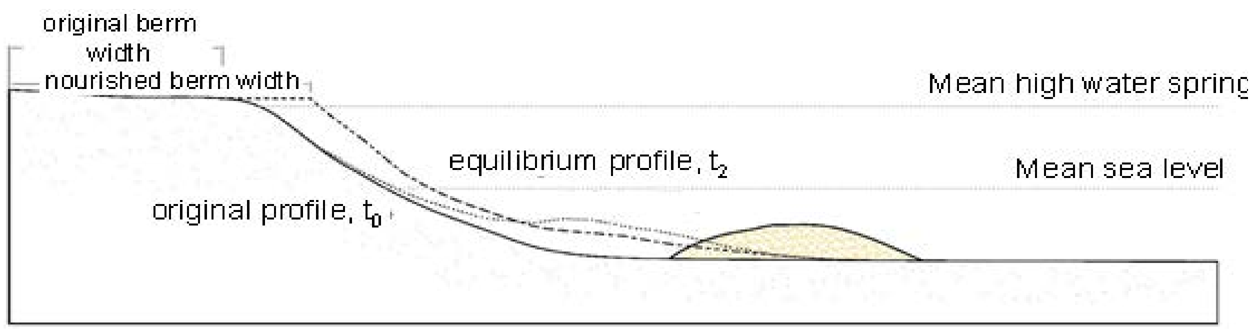


Figure 9. Typical Nourishment Profiles: Subaqueous Sandbar Nourishment[8]

(Source: Qi et al., 2021)

9.1.4 Layered Profile Design

Sandy beach restoration can utilize either single-layer or multilayer designs. When the restoration length is extensive and the volume of sand fill is substantial, a multilayer design is recommended. The grain size and sorting of the base layer can be larger than the designed grain size of the sediment, while the grain size and sorting of the surface layer should match the designed grain size of the sediment.

Gravel beaches should adopt a layered design, with a gravel filling structure composed of a three-layer mixed cross-section that includes an energy-dissipating layer on the surface, a permeable cushion layer, and a foundational layer.

9.2 Layout Design for Sandy Coast Restoration

Based on the coastal morphology and background sediment transport conditions, the plan design for sandy coast restoration projects includes three types of plan forms: headland–bay beaches, straight beaches, and artificial sand engine.

9.2.1 Layout Design for Headland-Bay Beaches

Headland–bay beaches are a common form of sandy coast that act as relatively independent sedimentary units. Influenced by the sheltering effect of headlands, these beaches are usually in a stable state (Figure 10). Such beaches typically develop on tectonically controlled active continental margins and are the most common beach type in China. For damaged headland–bay coasts, static equilibrium headlands can be constructed using structures (e.g., artificial headlands) to facilitate beach nourishment. The shoreline layout usually adopts the parabolic model proposed by Hsu and Evans[9], which includes adjusting the equilibrium plan form, determining the wave diffraction point in the project area based on the dominant wave direction, and identifying the starting point of the downstream straight segment of the static equilibrium beach (Figure 11). Specific engineering designs can use models such as MepBay[10] or MeePaSoL[11], which are based on equilibrium bay theory, to simulate and predict the plan form of the restored sandy coastline under the influence of normal waves.

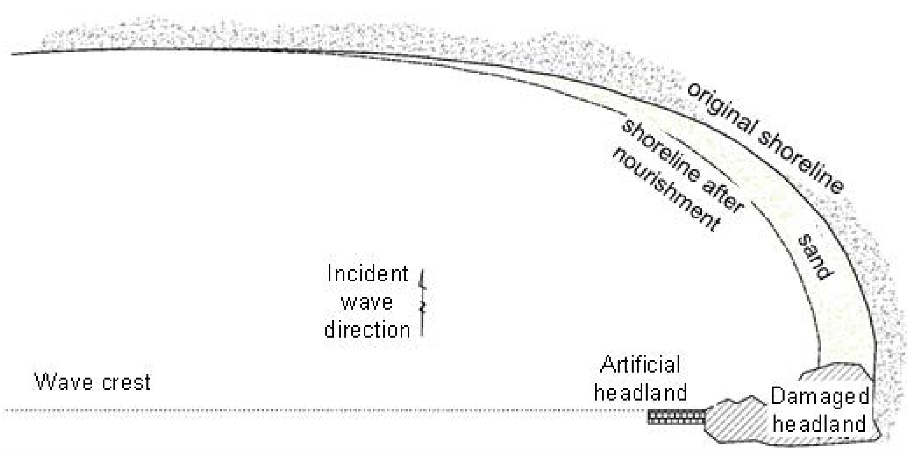


Figure 10. Layout Design for Headland-Bay Beaches[8] (Source: Qi et al., 2021)

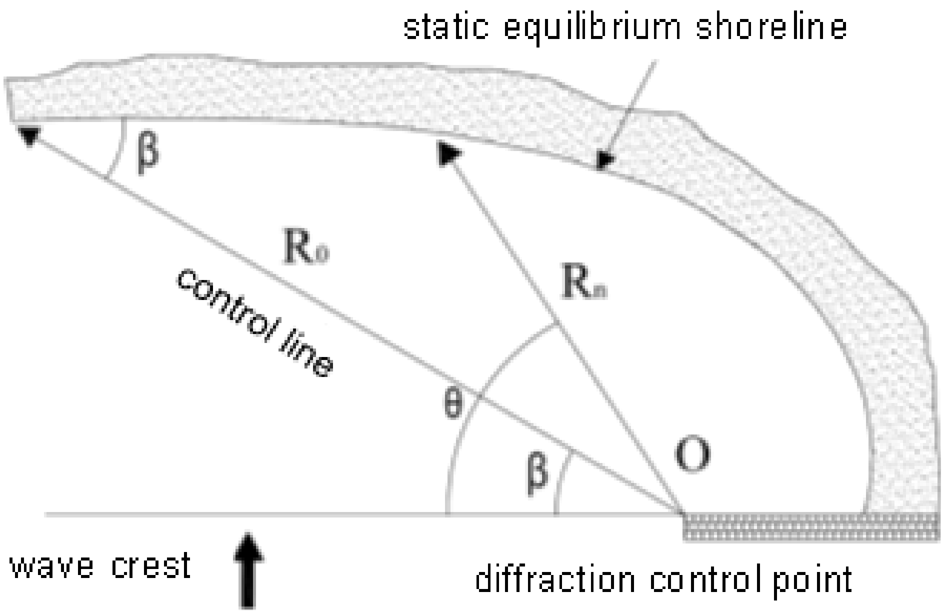


Figure 11. Static Equilibrium Headland–Bay Shoreline Design Based on Hsu and Evans[9]

(Source: Hsu & Evans, 1989)

The restoration of equilibrium headland–bay beaches has the advantage of minimal adjustment to the beach plan form, resulting in relatively stable shorelines. Once a stable state is established, it seldom requires further maintenance. However, the application of this method is limited by the natural development conditions of the coast. It is generally suitable for headland–bay coasts that have experienced headland damage, beach instability, or artificial destruction. This approach is not appropriate for creating headland–bay beach forms on locally straight coastlines.

9.2.2 Layout Design for Straight Beaches

For straight beaches with clear sediment transport chains upstream and downstream, alongshore sediment transport can lead to net sediment loss and continuous coastal erosion in cases of insufficient sediment supply, the presence of local structures, and sand mining (Figure 12). The most common restoration method for this type of beach is direct sand nourishment in the eroded locations, which is the most widely used method globally. This beach nourishment method is employed for most sandy beach restorations in the United States. Typically, this method involves multiple renourishment cycles combined with designated sand mining areas, with maintenance cycles generally ranging from 5 to 7 years.

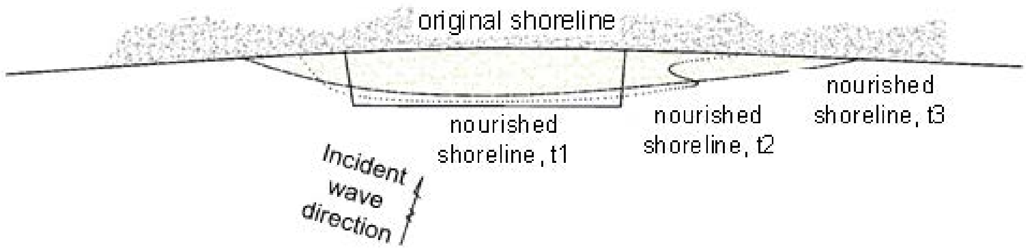


Figure 12. Layout Design for Straight Beaches[8] (Source: Qi et al., 2021)

Compared to headland–bay beaches, the alongshore sediment transport on straight beaches has a more pronounced impact on adjusting the restored beach plan form in the transition area between the restored and adjacent nonrestored sections. Beach nourishment involves the shoreline moving seaward, creating a transition area where the coastline's direction differs from that of the original shoreline. Sediment diffuses from the nourished beach to the adjacent nonnourished beach. Theoretically, a transition point forms where erosion and accretion balance, forming a stable shoreline (Figure 13). Therefore, to achieve a certain scale of rectangular nourished beaches, it is necessary to calculate the beach area that can be retained over a specific period. Analytical models, such as GENESIS and ONELINE, can be used for this calculation.

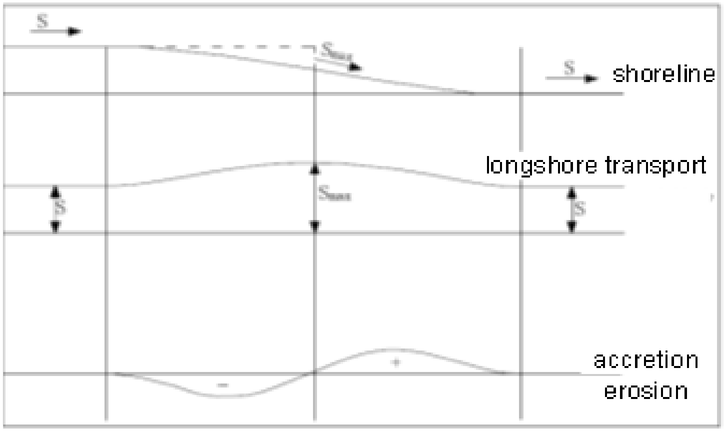


Figure 13. Schematic of the Diffusion Process at Both Ends of a Nourished Beach on a Straight Coast[4] (Source: Cai et al., 2015)

9.2.3 Design of Artificial Sand Engine

For sandy coasts with a distinct sediment transport background, a continuous sediment supply is necessary to maintain coastal equilibrium. This can be achieved by providing an artificial sand source upstream, allowing the sediment to move downstream through longshore currents, thereby mitigating downstream coastal erosion through natural processes (Figure 14). This method has been successfully applied on the Dutch coast (Figure 15). In 2011, 21 million cubic metres of sand was artificially placed on the North Sea coast, ensuring sufficient sediment supply for 10 kilometres of downstream coast over 20 years. This approach promotes dune and beach development, enhances coastal protection, creates habitats, and increases the potential for recreational development. This design method is also known as "sand engine".

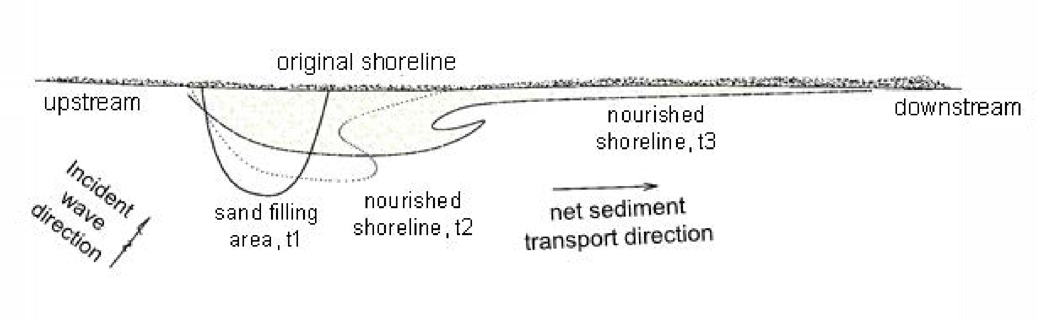


Figure 14. Design of Artificial Sand Engine[8] (Source: Qi et al., 2021)

Figure 15. Successful Sand Engine Nourishment Project in the Netherlands[12]
(Source: Stive et al., 2013)

9.3 Sand Filling Design for Sandy Coast Restoration

9.3.1 Several Considerations

The selection of sediment grain size is one of the most critical aspects of sandy beach restoration design. When designing sand nourishment characteristics for a restoration project, four main factors related to coastal protection and recreational tourism should be considered: beach stability, sediment dynamics, durability, and coastal recreational needs.

(1) Beach Stability

In their natural state, sandy coastal sediments are continuously undergoing sorting processes. Therefore, the grain size and grading characteristics of natural beach sediments in a specific area are the primary indicators of the material needed for beach stability. However, due to the limitations of sand sources for nourishment, it is challenging to achieve a perfect match between the nourishment sand and the original beach sand in terms of technology, budget, or feasibility.

Finer nourishment sand tends to form a gentler equilibrium profile slope, while coarser nourishment sand tends to form a steeper equilibrium profile slope. The equilibrium profile shape of the restored beach largely depends on the relationship between the grain size of the nourishment sand and the original beach sand. The corresponding relationships between different sediment grain sizes and typical beach face average slopes are shown in Table 8. Additionally, beaches composed of a certain grain size of sediment will form a gentler slope under strong wave dynamics and a steeper slope under weaker dynamic conditions.

Table 8. Relationships between beach profile slopes and sediment grain sizes under various wave conditions

Mean Grain Size (mm)	Moderate Wave Conditions Beach Slope Range	High Wave Conditions Beach Slope Range
0.2	1:50~1:100	1:50~1:100
0.3	1:25~1:50	1:45~1:55
0.4	1:15~1:25	1:40~1:45
0.5	1:10~1:15	1:35~1:40

If the nourishment sediment is coarser than the original beach sediment, beach coarsening will occur. Under conditions where it is challenging to alter the natural coastal erosion processes, coarser sediment is generally used for artificial beach nourishment to maintain a more stable restored beach. Coarser sediment nourishment is typically applied to severely eroded sandy coasts where it is difficult to provide effective protection for the backshore. Conversely, for sandy beaches with light erosion and a demand for high comfort levels, coarser nourishment is generally not recommended.

Coarser nourishment is usually applied in environments with strong nearshore dynamics and sediment transport. For instance, gravel-sized sediments can provide better protection for beach sections with notable alongshore currents and sediment transport, such as open coastlines. The disadvantage of coarser nourishment is that overly coarse sediment may affect the comfort of beachgoers and the habitat of local flora and fauna. Therefore, further studies must be conducted when choosing this approach.

(2) Sediment Dynamics

Once the sediment is placed, the nourishment sediment will be transported and sorted by wave and tidal actions. Particularly on sandy beaches, some fine-grained sediments may be lost due to bottom scouring and wind-driven sand transport on the beach surface. If the nourishment sediment is sourced from offshore and contains a high proportion of fine particles, the initial loss of fine-grained sediments could be significant. The erosion and loss of fine particles in the nourished area may have long-term impacts on nearby benthic organisms.

If the grain size distribution of the nourishment sediment is broader than that of the original beach sand, it generally performs worse than natural sand. This is partly because the nourishment sediment contains a higher proportion of fine-grained particles. Oversized sediment particles protruding from the beach surface tend to be transported offshore, whereas on a natural beach, the interlocking effect of sediments with different grain sizes protects the beach surface.

(3) Durability

The durability of beach sediments under continuous wave and tidal forces, including rounding and mass loss, depends on the mineral composition and morphology of the beach sediments. Generally, the main mineral components of sandy coastal sediments in China are quartz, feldspar, and mica. Currently, most nourishment sand used for the restoration of sandy beaches in China comes from nearshore areas and rivers and thus has a relatively high degree of rounding. As a result, the mass loss rate due to particle rounding is relatively low, whereas the mass loss rate for irregular sediment particles (such as gravel fragments) due to rounding is relatively high.

The shell content in the nourishment sediment is critical for beach durability, as shells break down quickly, have a low density and are thinner in shape, making them more susceptible to wind transport. The clay component in the sediment is easily eroded and transported in suspension.

(4) Coastal Recreational Needs

For tourist beaches and recreational sandy beaches, there are certain requirements for the texture, colour, and mineral composition of the beach fill. Tourist beaches should have a comfortable texture that is suitable for walking and activities; the sand colour should be close to yellow or white to enhance visual appeal; and the nourishment sediment should have low clay and shell contents. Generally, the clay content in the nourishment sediment should be less than 0.2%, and the shell content should be less than 1%.

9.3.2 Impact of Sediment Grain Size on Postrestoration Beach Evolution

For sandy coasts, the ideal nourishment sediment for beach restoration should match the natural beach sediment. However, in most cases, the sand source areas are located offshore, where the lateral sorting process in the coastal zone results in sediment with a generally smaller grain size than the natural beach sand. Only a small portion of beach restoration projects use nourishment sand with a grain size that is equal to or larger than that of the natural beach sand. If the fill sand for beach restoration matches the original beach sand, the centroid of the restored beach plan can remain stable regardless of changes in the incident wave direction. The stability is due to the consistent alongshore sediment transport rate within the restoration area and the matching rates of sediment transport from upstream areas to the restoration area and from the restoration area to downstream areas.

As shown in Figure 16, the transport coefficient decreases with increasing sediment grain size. If the nourishment material for the beach restoration project is coarser (or finer) than the natural beach sand, the sediment transport rate within the restoration area will no longer equal the sediment transport rate from upstream areas to the restoration area and from the restoration area to downstream areas. When the grain size of the fill sand is smaller than that of the natural beach sand, the sediment transport rate from upstream areas to the restoration area is less than the transport rate within the restoration area, leading to the centroid of the restored beach plan shifting downstream, thereby affecting the postrestoration beach plan evolution.

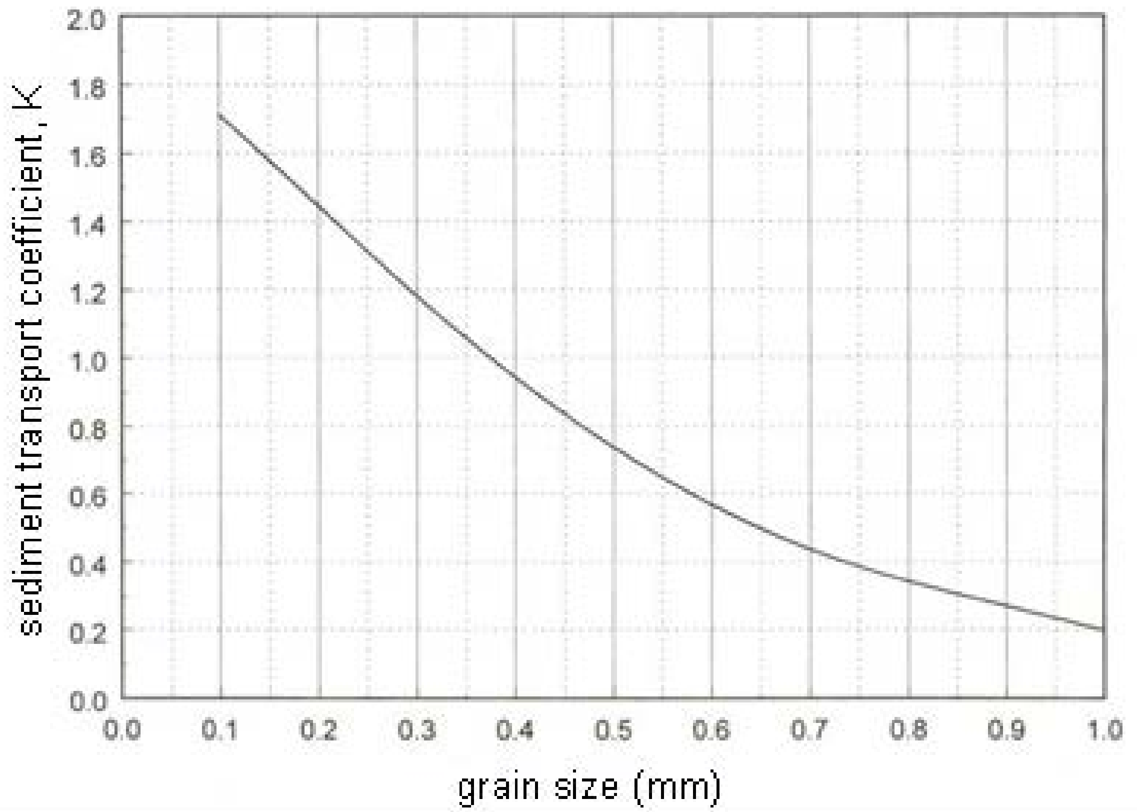


Figure 16. Relationship between the sediment transport coefficient and median grain size (D_{50})[4]

9.4 Design of Auxiliary Structures

9.4.1 Common Types and Design Principles

(1) Sand-Trapping Groynes

Sand-trapping groynes can be classified into two functional types: complete trapping and partial trapping.

——**Complete Trapping.** These structures should be constructed at the downstream end of the alongshore sediment transport direction of the restored coast and should align with the shoreline to form an artificial headland. It is recommended that the angle between the primary wave direction and the sand-trapping groyne be 100° to 110° . The optimal length of the groyne in the water should be 40% to 60% of the distance from the shoreline to the breakpoint.

——**Partial Trapping.** These structures are usually located at the end of sandy coast restoration areas. They achieve local adjustment of the beach by trapping sand, enhancing the geomorphological stability of the restored beach section, and ensuring the natural continuity of sediment transport downstream.

(2) Offshore Breakwaters

Offshore breakwaters can be classified into two types: emergent breakwaters and submerged breakwaters.

——**Emergent Breakwaters.** The design of emergent breakwaters should consider the relationship between shoreline evolution behind the breakwater and influencing factors, as described by the following formula:

$$\frac{X_S}{B} = f(H_0/L_0, S/B, \tan\theta, \alpha, G_o, \gamma)$$

where

X_S is the length of the sand spit behind the breakwater, measured in meters (m);

B is the length of the breakwater, measured in meters (m);

H_0 is the deepwater wave height, measured in meters (m);

L_0 is the deepwater wavelength, measured in meters (m);

$tan\theta$ is the beach slope;

S is the offshore distance, measured in meters (m);

α is the wave direction near the breakwater, measured in degrees (°)

G_0 is the opening width, measured in meters (m);

γ is the porosity of the breakwater structure (%).

When there is a sufficient upstream sediment supply, the ratio of the offshore distance X_B to the breakwater length L_B influences the sand spit formation behind the breakwater. When the ratio X_B/L_B is between 1 and 2, a sand spit extending from the shore to the sea will form behind the breakwater. When X_B/L_B<1, the sand spit will develop into a tombolo.

——**Submerged Breakwaters.** The crest elevation of submerged breakwaters should be below the lowest low tide level, making them suitable for coastal areas with small tidal ranges.

It is recommended that the transmission coefficient of the submerged breakwater at mean low tide be between 0.2 and 0.3 and should not be lower than 0.6 at mean high tide. The relationship between the wave transmission coefficient of the submerged breakwater and the height of the breakwater crest above the calculated water level should comply with the specifications of JTS 154.

(3) Artificial Headlands

Artificial headlands modify the wave diffraction point to alter incoming waves along the coast and, combined with sand nourishment, can create stable headland–bay beaches.

Artificial headlands are suitable for static headland–bay coasts and should help form a static headland–bay morphology without disrupting the original headland–bay shape or existing beach stability. They are not suitable for the restoration of straight coastline beaches. When conditions permit, artificial headlands should be integrated with ecological structures such as fish reefs and oyster reefs using environmentally friendly materials.

(4) Sediment Bypassing

When natural sediment transport along coastal areas is obstructed by features such as rivers, navigation channels, or jetties, sediment bypassing systems should be designed to connect upstream and downstream coasts. This ensures the natural flow of the coastal sediment transport chain, maintaining the stability and equilibrium of downstream beaches.

Two common methods for constructing sediment bypassing systems are the use of conventional pumps and jet pumps.

9.5 Backshore Vegetation Restoration Strategy

9.5.1 Plant Selection

The specific requirements for plant selection are as follows:

——Plants should be wind-resistant, salt-tolerant (both soil and spray), drought-resistant, and able to thrive in poor soil conditions. Suitable plants can be found in Appendix C of HY/T 0304.

——Woody plants should be the primary choice and can be supplemented with a mix of trees, shrubs, and grasses. The groundcover plants should be perennials, with annuals as a secondary choice.

—— Priority should be given to nitrogen-fixing plants, along with a suitable selection of plants possessing "flowering," "colourful," and "fragrant" attributes.

——Without damaging wild plant resources, rare and endangered plants should be preferentially selected.

——The domestication and propagation of native plants not currently available on the market are encouraged and their application should be promoted.

9.5.2 Soil Improvement

Soil improvement includes natural recovery-based improvement and landscape construction-based improvement. The requirements should follow the provisions of section 7.2 in HY/T 0304.

9.5.3 Plant Configuration

The specific requirements for vegetation configuration are as follows:

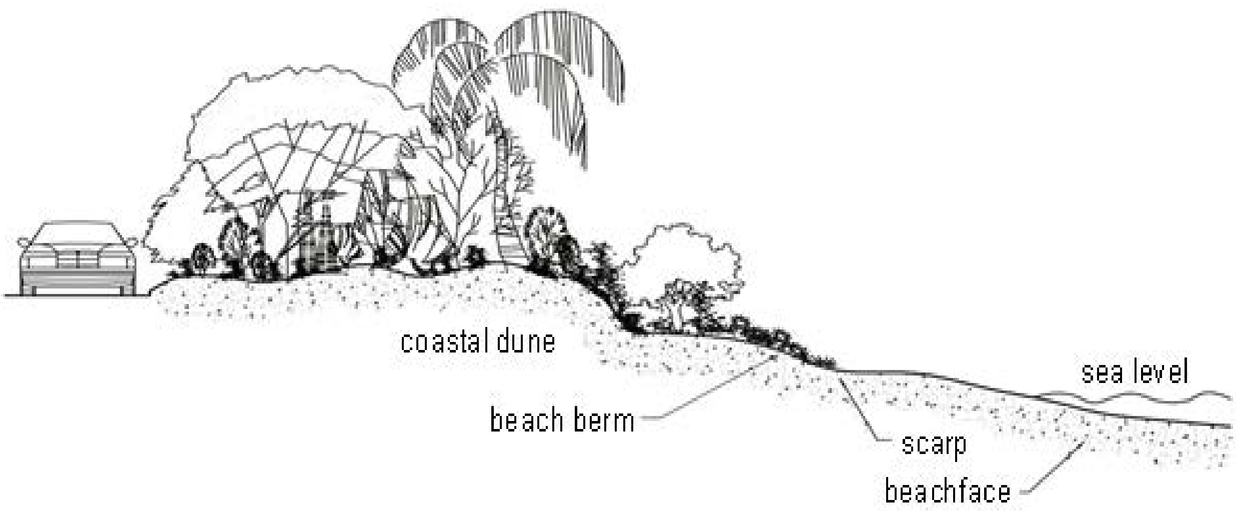
a) For windbreak and sand fixation, as well as coastal protection, large-scale planting of suitable species is usually selected. The trees and shrubs at windward positions should comply with the requirements of LY/T 1763-2008.

b) For the construction of ecological landscapes, the design should consider the following aspects:

——Scientific configuration of evergreen and deciduous plants, backbone and base plants, and fast-growing and slow-growing plants should be performed;

——The design should meet both aesthetic needs and ecological restoration functional requirements in order to construct a coastal plant community landscape;

——Different species should be planted according to site conditions to form a diverse and layered plant community with surrounding landscape. From the sea to the land, the backshore vegetation community of sandy coast can be divided into four to five lines of defence.



Plant Configuration Mode for the Backshore Vegetation Restoration of Chinese Sandy Coasts

A. Herbaceous Plant Communities

This model is mainly used as the first line of defence for the backshore areas of sandy coasts without tree or building cover to enhance vegetation coverage and visual appeal. The recommended plant configurations are as follows:

a) Tropical: Spinifex littoreus, Cyperus pedunculatus, Panicum repens, Ipomoea pes-caprae, Ipomoea brasiliensis, Crinum asiaticum;

b) Southern Subtropical: Spinifex littoreus, Cynodon dactylon, Imperata cylindrica, Ipomoea brasiliensis, Oenothera drummondii, Crinum asiaticum;

c) Central Subtropical: Oenothera drummondii, Cynodon dactylon, Imperata cylindrica, Zoysia japonica, Ipomoea brasiliensis, Cakile maritima;

d) Northern Subtropical: Spinifex littoreus, Zoysia japonica, Polygonum aviculare, Canavalia maritima, Portulaca Pilosa;

e) Temperate: Limonium sinuatum, Carex pumila, Elymus mollis, Ammophila breviligulata, Polygonum aviculare, Sonchus oleraceus, Sedum aizoon.

B. Shrub and Groundcover (Grass) Communities

This model is mainly used as the second line of defence for sandy coastal backshore areas, where shrub and grass communities are used to provide transitional, three-dimensional, and layered buffering effects, enriching the landscape. The recommended plant configurations are as follows:

a) Tropical: Cyperus pedunculatus, Spinifex littoreus, Ipomoea brasiliensis, Vitex trifolia, Scaevola taccada, Acanthophoenix rubra, Pandanus tectorius;

b) Southern Subtropical: Spinifex littoreus, Cynodon dactylon, Imperata cylindrica, Ipomoea brasiliensis, Oenothera drummondii, Scaevola taccada;

c) Central Subtropical: Imperata cylindrica, Carex humilis, Polygonum aviculare, Vitex trifolia, Hibiscus hamabo;

d) Northern Subtropical: Spinifex littoreus, Cakile maritima, Ipomoea brasiliensis, Vitex trifolia, Yucca filamentosa, Pittosporum tobira;

e) Temperate: Carex kobomugi, Cynodon dactylon, Vitex trifolia, Leymus mollis, Ziziphus jujuba, Tamarix chinensis, Pinus thunbergia.

C. Tree and Groundcover (Grass) Plant Communities

This model is mainly used as the third and fourth lines of defence in sandy coastal areas. It employs tall trees combined with various groundcover (grass) plants to create open plant spaces, providing visually simple landscapes and good sightlines. The recommended plant configurations are as follows:

a) Tropical: Crinum asiaticum, Cyperus pedunculatus, Sesuvium portulacastrum, Tournefortia argentea, Morinda citrifolia, Pittosporum tobira;

b) Southern Subtropical: Portulaca pilosa, Ipomoea brasiliensis, Crinum asiaticum, Cocos nucifera, Terminalia catappa, Hibiscus tiliaceus, Mallotus japonicus;

c) Central Subtropical: Cakile maritima, Ipomoea pes-caprae, Polygonum aviculare, Pistacia chinensis, Celtis sinensis, Ficus macrocarpa;

d) Northern Subtropical: Pennisetum purpureum, Oenothera drummondii, Verbesina encelioides, Celtis sinensis, Melia azedarach, Sapium sebiferum, Phoenix canariensis;

e) Temperate: Leymus mollis, Zoysia japonica, Artemisia vulgaris, Elaeagnus angustifolia, Morus mongolica, Ulmus macrocarpa, Ailanthus altissima, Pistacia chinensis.

D. Tree, Shrub, and Groundcover (Grass) Plant Communities

This model is mainly used as the fifth line of defence in sandy coastal areas and utilizes plant form and seasonal phases to create layered plant configurations through vertical arrangement and spatial organization. The upper layer consists of light-loving tall trees, including conifers and broadleaf trees, featuring species that exhibit spring and autumn colour changes. The middle layer includes partial-shade-tolerant small trees and flowering shrubs, with shade-tolerant species placed under the canopy and light-loving species placed at the edges. The lower layer features shade-tolerant groundcover and herbaceous plants. In dense forest areas, a balanced mix of trees, shrubs, and grasses enriches the landscape. The recommended configurations are as follows:

a) Tropical: Ipomoea brasiliensis, Sesuvium portulacastrum, Scaevola taccada, Dracaena cochinchinensis, Mallotus japonicus, Cocos nucifera, Tamarindus indica;

b) Southern Subtropical: Crinum asiaticum, Portulaca pilosa, Murraya paniculata, Ficus microcarpa, Nerium oleander, Erythrina variegate;

c) Central Subtropical: Catharanthus roseus, Nerium oleander, Casuarina equisetifolia, Jasminum sambac, Araucaria heterophylla, Erythrina variegate;

d) Northern Subtropical: Portulaca pilosa, Catharanthus roseus, Nerium oleander, Ligustrum sinense, Yucca filamentosa, Ardisia crenata;

e) Temperate: Lolium perenne, Gaillardia pulchella, Pittosporum tobira, Lycium barbarum, Euonymus japonicus, Juniperus horizontalis, Pinus thunbergii, Juniperus chinensis 'Kaizuka'.

9.6 Coastal Dune Restoration Strategy

Backshore dunes are important geomorphological units of sandy coasts. They provide "soft" protection against extreme marine dynamics and offer valuable habitat space for coastal flora and fauna. The restoration of backshore dunes includes key design elements such as dune restoration morphology, restoration height, dune toe elevation, structural materials, and dune vegetation. A schematic diagram of dune restoration is shown in Figure 17, where Z_1, Z_2, and Z_3 represent the crest elevations of different dunes; Z_4 indicates the windward slope toe elevation of the seaward-facing first dune; H_1, H_2, and H_3 indicate the restoration heights of different dunes, measured as the elevation difference from the dune crest to the slope toe; and MHWS represents the mean high water spring tide level over many years.

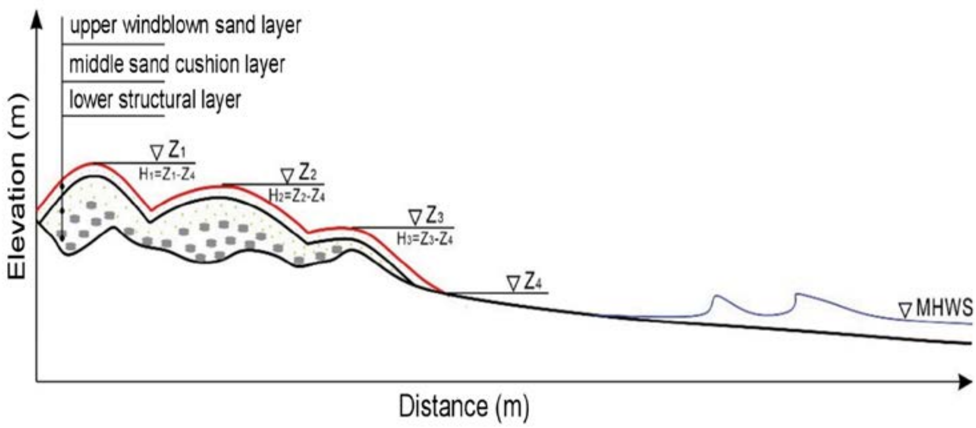


Figure 17. Schematic design of coastal dune restoration

Dune Restoration Morphology. Borrowing from the natural development characteristics of coastal dunes, restored dunes should ideally adopt an undulating "multi-crest" morphology. From an aeolian geomorphology perspective, a multi-crest shape helps reduce sediment transport rates and represents a dynamic equilibrium state that adapts to and responds to wind dynamics.

Dune Restoration Heights. In a set of multi-crest restoration dunes, the first landward dune should have the highest hazard prevention and mitigation levels. The design height H_1 (where $H_1 = Z_1 - Z_4$) should be determined by considering both the coastal protection requirements under extreme hydrodynamic conditions and the natural growth and development patterns of coastal dunes. If the current coastal height threshold to withstand a 50-year extreme high water level combined with a 50-year wave condition is h_1 and the preserved natural dune height in the same or an adjacent bay is h_2, the restoration height H_1 should be greater than the other two values, i.e., $H1=max(h_1,h_2)$. In contrast, the first seaward-facing dune has the lowest hazard prevention and mitigation requirements. The design height H_3 (where $H_3=Z_3 \sim Z_4$) should correspond to the current coastal height threshold to withstand a 10-year extreme high water level combined with a 10-year wave condition.

The restoration height of the middle dune H_2 should be between H1 and H3 and can be calculated as the average of the two, i.e., $H_2=(H_1+H_3)/2$.

Seaward Dune Toe Elevation. According to the natural development characteristics of coastal dunes, the toe of the seaward dune (Z_4) typically lies above the mean high water spring (MHWS) tide line, combined with wave run-up (R); therefore, $Z_4=MHWS+R$. The wave run-up (R) can be calculated using the formula specified in the "Specifications for Hydrology of Ports and Waterways" (JTS 145-2015).

Dune restoration structure and materials: A three-layer structure is used, arranged from top to bottom as follows: an upper windblown sand layer, a middle sand cushion layer, and a lower structural layer. The upper windblown sand layer is approximately 0.2 m thick and composed of well-sorted fine sand, with a grain size and composition close to those of the natural dune sand. The middle sand cushion layer is approximately 1 m thick and composed of medium to fine sand, with qualities close to those of the natural beach sand. The lower structural layer is primarily for maintaining the overall stability of the dune's shape and can be constructed using sandbags, with the quality of the fill sand being somewhat low.

Dune vegetation restoration: On the basis of dune restoration, a multilayered dune vegetation system combining trees, shrubs, and grasses should be established. Specifically, sand-tolerant vines or herbaceous plants should be planted on the windward side of dunes to form the first sand-fixing barrier and beautify the coastline. Salt-tolerant and wind-resistant shrubs should be arranged in rows on the dune crest to form a windbreak and further stabilize the dune. A forest belt should be cultivated behind the dune to improve the regional wind and sand flow field structure. The selected plant species should primarily be native plants that are wind resistant, salt tolerant, drought tolerant, and able to thrive in poor soil and salt spray conditions, balancing ecological function and landscape value.

10. Follow-up Monitoring, Effect Assessment and Adaptive Management

10.1 Monitoring of Restoration Projects

10.1.1 Monitoring the Stability and Evolution of Restored Sandy Coasts

Monitoring the stability and evolution of restored sandy coasts begins with establishing a measurement benchmark. If a benchmark from the preliminary survey is available, it can be used directly. Otherwise, a new benchmark should be established as a reference point for future coastal geomorphological monitoring. The general elements of monitoring beach evolution include profile and topography measurements, offshore profile and underwater topography measurements, sediment evolution, and aerial/remote sensing image analysis. Depending on the monitoring objectives, meteorological data and wave data may also be needed. It is not necessary to include all monitoring content in a single monitoring plan. To evaluate the impacts and results of the project, monitoring should be conducted both before and after project construction.

(1) Establishing a Measurement Baseline

Before implementing the monitoring plan, a measurement baseline must be established to monitor physical changes in the beach. Based on the geomorphological characteristics of sandy coast restoration projects in China, the measurement baseline is generally set at the artificial revetment (if the beach is backed by an artificial revetment), the top of the fixed vegetated dune (if the beach is backed by dunes), the top of the sea cliff (if the beach is backed by a sea cliff), or on artificial structures. Fixed and relatively safe reference points (stakes) should be established at these locations, with absolute elevations and coordinates derived from nearby known points.

(2) Beach Morphology Monitoring

Measuring the profile and topography of a beach is the core of evolution monitoring and can be completed using various methods. A high measurement accuracy is needed, and consistency with historical data in terms of reference benchmarks and precision is essential to enable accurate comparative analysis of changing characteristics. Therefore, attention should be given to these aspects during actual measurements. The main content and basic requirements for beach morphology monitoring are shown in Table 9.

The spacing of the monitored profiles and survey frequency should align with the spatial and temporal evolution process of the project design. For most projects that are approximately 1-2 km long, a profile spacing of approximately 200-400 metres generally fulfils measurement needs. Importantly, shoreline and coastal morphology can undergo significant changes due to restoration activities, particularly near the ends of beach restoration projects. Therefore, when establishing monitoring profiles, it is vital to ensure that monitoring sections are positioned in the middle of the project area. In areas where there are substantial changes or unique shoreline features, monitoring should be increased as necessary. Additionally, the spacing of profiles within and around the project can be adjusted based on the changes in the restoration project, available monitoring resources, and objectives, especially regarding the intended use of monitoring results. Based on previous experience, some projects have implemented 5-10 monitoring profiles at the ends and surrounding areas of a project. The frequency of profile monitoring should be in line with the project's evolution within the designated time scale of the project's design.

Comprehensive topographic monitoring of the beach aims to comprehensively reflect postrestoration geomorphological changes, including erosion hotspots, sediment balance, and erosion–deposition changes. Compared to profile monitoring, comprehensive topographic surveys are conducted less frequently, typically once immediately after construction and once annually thereafter. These comprehensive topographic surveys should be compared with the beach's prerestoration topography and combined with the results from profile monitoring to analyse postrestoration beach evolution and stability.

Underwater profile and topography monitoring of the beach restoration area expands and enhances beach monitoring efforts. The diffusion and deposition of sediment from the restored beach can lead to changes in underwater topography, especially in an independent headland–bay coastal unit with significant underwater topography changes. Monitoring underwater profiles and topography aids in understanding the sediment transport and deposition patterns of the restored beach. Considering monitoring costs and efficiency, underwater topographic surveys should be conducted at least once annually for three years after project construction, with the lateral range of underwater topographic measurements extending to the closure depth. The monitoring of shoreline changes is one of the core aspects of monitoring sandy coast geomorphological evolution. Shoreline accretion or erosion is the most visible change on a beach and serves as a critical indicator for coastal managers, investors, and the public. It visually reflects the evolution process of a beach and is an essential measurement for evaluating beach stability. Therefore, shoreline monitoring should commence promptly after implementing the restoration project. During the initial year following construction, monitoring should be conducted frequently, particularly within the first six months when significant shoreline changes and adjustments occur. Monitoring should occur at least once every two months.

Table 9. Contents and Requirements for Postrestoration Beach Morphology Monitoring

Item	Requirements
Beach Profile	Measuring Range: From the backshore of the restoration area to the mean spring low water. Profile Setup: Ensure postmonitoring profiles coincide with prerestoration profiles, set profiles perpendicular to the shoreline, with a density of no less than 5 profiles per kilometer, and fix the reference points. Measuring Frequency: During the first year after construction, at least quarterly, with additional measurements after storm surges; thereafter, at least twice a year; the frequency of comprehensive topographic surveys should match the profile monitoring frequency. Measuring Technical Requirements: Follow the "Specifications for Marine Engineering Topographic Survey" (GB17501-2017).
Nearshore subaqueous topography	Measuring Range: Extend seaward from the restoration area to the closure depth. Profile Setup: Extend seaward from the origin point and direction of the beach monitoring profiles. Measuring Frequency: At least once a year for the first three years after construction. Measuring Technical Requirements: Follow the "Specifications for Oceanographic Survey" (GB/T 12763.2-2007).
Shoreline Change	Measuring Range: Shoreline within the coastal unit of the restoration area. Measuring Frequency: During the first six months after construction, every two months; during the second six months, at least quarterly, with additional measurements after storm surges; thereafter, at least once a year. Measuring Technical Requirements: Follow the "Specifications for Marine Engineering Topographic Survey" (GB17501-2017) to collect historical shoreline comparison data and understand past shoreline changes.
Backshore height	Measuring Range: Position and elevation of the highest point of berm and dune in the frontier edge of backshore on sandy coasts; position and elevation of the crest of seawall for beaches without dunes or berms Measuring Frequency: The primarily survey should be completed within 2 months before the storm, and post-storm survey should be completed within 5 days after the storm Measuring Technical Requirements: Comply with the standard 10.2 of GB/T 17501-2017

Item	Requirements
Erosion hotspot	Measuring Range: Erosion cliff on backshore, scouring zones in front of seawalls, nearshore intense evolution areas caused by coastal structures and anthropogenic perturbations Measuring Frequency: The follow-up repeated survey is completed within 5 days, at 1 month and 3 months after storm respectively Measuring Contents: Range and height of backshore cliff, range and quantity of erosion hotspot

(3) Sediment Change Monitoring

To ensure adherence to the design plan, sand samples are customarily collected prior to undertaking any restoration work. These samples serve to identify the characteristics of the original beach and the source area of the sand. The number and placement of sand samples taken from the original sandy coast may vary, but it is essential that the sampling locations within a profile include the dunes, berms, beach face, and points beyond 25% of the calculated closure depth at specific depths or distances. Typically, samples are collected at 1-metre elevation intervals, with the general principle being to conduct sampling at least every other profile. Following restoration work, it is also necessary to conduct sampling and analysis based on the monitoring objectives. For example, if there is a noticeable disparity between the natural sand and the restoration sand or if the restoration sand exhibits poor sorting, collecting and analysing samples can help document any changes in the restoration sand, as well as the time required for the restoration sand to assimilate with the natural sand under dynamic nearshore conditions. As a general rule, sand sample collection should occur shortly after the restoration work has been completed. Based on current practices, sediment sampling is typically performed in conjunction with topographic monitoring. The specific requirements for sand sample collection are outlined in Table 10.

Table 10. Contents and Requirements for Sediment Change Monitoring After Restoration

Items	Requirements
Sediments	Station Settings: a) The sediment survey profile is consistent with the topography survey profile, and one surface sediment sampling point should be set up at representative locations such as dune, berm, high tide zone, middle tide zone and low tide zone respectively; b) No less than 3 intertidal zone survey stations should be set if the width of intertidal zone is shorter than 200m. No less than 5 intertidal zone survey stations should be set if the width of intertidal zone is longer than 200m; c) The principle of subaqueous sediment survey is one station every 500m. Sampling Depth: 5~20cm beneath the surface. Sampling Frequency: Keep pace with topography survey
Boundary between sand and mud	Survey Method: Obtain the planimetric position and elevation of the sand-mud transition by using high precision measuring equipment. Survey Frequency: Not less than once in summer and winter within recent 2 years. Position: Beach surface sediment at sand-mud transition

(4) Remote Sensing Image Monitoring

Remote sensing imagery is a more intuitive and efficient method than profile measurements or other types of surveys. Remote sensing interpretation provides comprehensive information about the progress of a project, particularly the width of the dry beach, which is easily understood by the general public. High-quality images captured during low tide serve as a basis for estimating the width of the dry beach. The use of aerial imagery is cost-effective, and images are typically obtained before and after restoration and are used in conjunction with colocated profile measurements for related purposes.

10.1.2 Monitoring the Restored Coastal Environment

Restored coastal environments can undergo changes in various aspects, such as coastal dynamics, water quality, benthic organisms, backshore vegetation, sand colour, and sediment suitability. The significance of these characteristics varies among different restoration projects. Typically, environmental monitoring of restored beaches includes hydrodynamic environment monitoring, water quality monitoring, benthic organism monitoring, and backshore vegetation monitoring. In contrast, targeted monitoring of sand colour and environmental suitability is less common.

(1) Monitoring of Coastal Hydrodynamic

Restoration projects focusing on sandy coasts often have an impact on the local nearshore hydrodynamic environment. Alterations in coastal topography and beach nourishment, for instance, inevitably affect the wave field, current field, and suspended sediment concentration in nearby areas. Details of the content and requirements for coastal hydrodynamic monitoring are outlined in Table 11.

Table11 Contents and requirements for coastal hydrodynamic survey after restoration

Items	Requirements
Waves	Monitoring time: a) The continuous monitoring of deep-water wave conditions in a typical season of not less than one month in recent five years; b) During storm surges Monitoring bathymetry: a) The bathymetry of 10-20m near the coast is appropriate; b) The intertidal and nearshore shallow water wave conditions during the storm Monitoring techniques: a) Comply with the section standard 7 of GB/T 14914.2-2019; b) The seabed dynamic observation should be carried out in the area of 10-20m nearthe target beach before the storm, ADCP (Nortek) and RBR water level gauges can be used to measure wave, current and water level data in the targeted area; Notes: The selection of monitored beach profile should be typical, generally in the middle zone of the whole sandy coast, and far from the erosion hotspot and artificial structures. The methods of wave observation in intertidal zone and nearshore shallow water are as follows: arranging observation arrays consisting three tide gauges, covering subtidal zone, intertidal zone and supratidal zone (in the front of seawall), the elevation difference between adjacent instruments: 0.1~2.0m, measuring frequency: 2~4Hz.
Maximum overwashing height during storm	Monitoring timing: Post-storm monitoring Monitoring methods: Combination of field observation and UAV remote sensing

Items	Requirements
Ocean currents	Monitoring timing, station settings and technology requirements comply with the table 2.
Suspended sediments	
Tidal levels	
Winds	
Regional sea level	

(2) Water Quality Monitoring

Given the growing recognition of the importance of environmental quality, particularly for sandy coasts used as popular seaside resorts, strict requirements are placed on water quality. Consequently, monitoring of the marine environment near the project, especially within the first six months after completion, should be intensified. The design of routine monitoring plans should consider the characteristics of the coast. The specifics of the content and requirements for water quality monitoring are provided in Table 7.

(3) Monitoring of Benthic Organisms

Sandy coast restoration projects can potentially impact benthic organisms within the restoration area. These impacts can be either short-term or long-term and need to be evaluated through postproject follow-up monitoring. Usually, benthic organism surveys are conducted in the spring and autumn within 1-2 years after the completion of construction. Details regarding survey elements, density, and technical requirements are presented in Table 6.

(4) Backshore Vegetation Monitoring

The composition of species, community structure, and changes in the distribution area/coverage of backshore vegetation are important indicators for assessing the ecological benefits of sandy coast restoration. Typically, follow-up surveys of backshore vegetation are conducted before construction and within 1-2 years after construction. Table 5 provides details on the survey elements and technical requirements.

10.2 Restoration Effect Assessment

The effectiveness evaluation of sandy coast restoration projects (postproject evaluation) includes four aspects: disaster damage evaluation, evaluation of disaster mitigation, evaluation of stability of beach nourishment, and evaluation of ecological effect. By conducting these evaluations, the ecological and hazard mitigation benefits of restoration projects can be understood, the protective and restoration effects of the projects can be comprehensively assessed, and management strategies can be proposed.

10.2.1 Disaster damage evaluation

10.2.1.1 Evaluation index

Damage evaluation index for sandy coasts is shown in Table 12.

Table 12 Damage evaluation index for sandy coasts

Index		Types	Damage degree		
			Low	Medium	High
Coastline position	The variation of the mean spring tide, which is negative for erosion and positive for deposition	Major index	Advanced deposit or stable	Erosion retreat distance is 5%~25% of the original dry beach width	Erosion retreat distance is more than 25% of the original dry beach width

Index		Types	Damage degree		
			Low	Medium	High
Seawall frontier/ backshore elevation	The mean elevation of natural backshore such as dune and berm, or the elevation of foreshore of the seawall, adopts the difference value from the pre-disaster, the down-erosion is negative, and the up-accretion is positive	Major index	Up-accretion or stable	Local down-erosion	Overall down-erosion
Intertidal slope	Beach slope from mean high tide level to mean low tide level, represented by "vertical variance/horizontal distance"	Secondary index	Getting mild	Fixed	Getting steeper
Erosion hotspot	The number or proportion of erosion hotspots along the shoreline	Secondary index	None	Less than 2 hotspots and 10% of shoreline	More than 2 hotspots and 10% of shoreline
Sediment grain size	Sediment grain size in dune or berm, high tide zone, middle tide zone and low tide zone	Secondary index	Almost unchanged	Locally coarsen	Overall coarsen

10.2.1.2 Evaluation methods and results

Taking the north or east of the sandy coast as the benchmark, each 200m of the sandy coast is taken as an evaluation unit. According to the comparison of the before and after changes of the evaluation index, the damage of the sandy coast is determined and divided into three levels of destroyed, damaged and stable. The details are as follows:

a) When one of the major indexes has a high degree of damage, the unit is determined to be destroyed;

b) When the damage degree of the two major indexes is not higher than medium, or one of the secondary indexes is greater than medium, the unit is determined to be damaged;

c) When the degree of damage of the two major indexes is low, and the secondary indexes are high, the unit is determined to be stable;

d) The first tracking survey should be conducted within 15 days after storm to evaluate the damage to the sandy shorelines caused by the storm;

e) Surveys should be conducted one month and three months after the storm to evaluate the recovery of the sandy coast and to determine the extent of irreversible damage to the sandy coast resulting from the storm disaster.

10.2.2 Evaluation of disaster mitigation

The evaluation of disaster mitigation capacity of sandy coasts primarily evaluates the ability of sandy coasts to resist waves and storm surges. Evaluation indicators include wave dissipation rate and Overwashing height.

10.2.2.1 Evaluation index

(1) Wave dissipation rate

Wave dissipation rate is calculated as the percentage of the wave height attenuation (H_1-H_2) to the original wave height H1 after the wave height H_1 propagates through a beach with width L:

$$R_{wL} = \frac{H_1 - H_2}{H_2} \times 100\%$$

in which:

R_{wL} -- wave dissipation rate;

H_1 -- wave height outside of breaker zone, unit: m;

H_2 -- wave height inside of breaker zone, unit: m.

(2) Overwashing height

The difference between the highest water level and the dry beach elevation when the highest water level exceeds the dry beach elevation during a storm.

10.2.2.2 Evaluation methods

Wave dissipation rate in sandy coast disaster mitigation can be determined by filed observation, empirical formulas, physical experiments and numerical modellings, see Appendix A of the "Technical guideline on coastal ecological rehabilitation for hazard mitigation—Part 7: Sandy Coast" for details.

10.2.2.3 Evaluation results

According to the selected method, combined with the relevant data obtained from measurement or calculation, the formula proposed in 10.2.2.1 is used to calculate the wave dissipation rate of sandy coast. The evaluation results can be divided into four grades according to the wave dissipation rate: excellent, good, medium and poor. For the same wave level, the higher the wave dissipation rate, the better the disaster mitigation effect and the higher the evaluation grade (see Table 13). This evaluation grade is related to the overwashing height. If the overwashing height is negative, the parameter value is 100%, and all wave energy is dissipated before reaching shoreline or dike.

Table 13 Disaster mitigation ability of sandy coast with different wave level and wave dissipation rate

Wave dissipation rate	Small waves (0.5 ⩽ H1/3<1.25)	Medium waves (1.25 ⩽ H1/3<2.5)	Large waves (2.5 ⩽ H1/3<4.0)
100%	Excellent	Excellent	Excellent
⩾ 80%~<100%	Good	Good	Excellent
⩾ 60%~<80%	Medium	Good	Good
⩾ 40%~<60%	Poor	Medium	Good
⩾ 30%~<40%	Poor	Poor	Medium
<30%	Poor	Poor	Poor

10.2.3 Evaluation of stability of beach nourishment

10.2.3.1 Evaluation index

The restoration of sandy coast focuses on habitat restoration, and its stability is the fundamental factor that determines its ecological function. In this part, a beach nourishment stability index system is constructed based on natural dynamic conditions, beach physical characteristics and beach adaptability, including 11 indexes. The interpretation and data resources of the evaluation index are shown in Table 14.

Table 14 The interpretation and data resources of the evaluation index

Category	Number	Index	Index interpretation	Data resources
Marine dynamic environment	1	Wave condition	Reflecting the wave energy acting on the beach and it is indicated by nearshore mean significant wave height	Wave station or buoy
	2	Storm intensity	Reflecting the influence of storms on beach, and it is represented by historical largest wave height	Historical meteorological statistics
	3	Storm frequency	Reflecting the frequency of storm actions, and it is represented by annual-average of effective storm numbers	Historical meteorological statistics

Category	Number	Index	Index interpretation	Data resources
Beach physical characters	4	Nourishment length	Length of nourishment in longshore direction	Field observation or image
	5	Nourishment grain size	Reflecting the grain size of beach nourishment, and it is indicated by the ratio between medium grain size of currently surface sediment and original beach sands or adjacent beach sands	Field observation
	6	Sands supply per unit width	Reflecting sands supply intensity, and it is represented by the sands filling volume on per unit width of beach	Data collection
Beach physical characters	7	Beach layout	Reflecting the refraction processes of nearshore waves and exposure of the beach to wave action	Field observation or image
	8	Auxiliary structure	Reflecting the influence of nearshore structures on wave attenuation and refraction, and the interception of longshore sediment transport	Field observation or image
Beach adaptation	9	Width of intertidal zone	Reflecting the effective zone of nearshore wave dissipation, and it is indicated by the horizontal distance between mean high tide level and mean low tide level in cross-shore direction	Field observation
	10	Width of dry beach	Reflecting the capacity of beach to encounter erosion, and it is represented by horizontal distance from backshore dune or seawall frontier to mean spring high tide level	Field observation or image
	11	Erosion hotspot density	Reflecting the local beach features, and is indicated by the number of erosion hotspot on per unit width of beach	Field observation

According to the stability of beach nourishment from high to low, the indexes are divided into 5 grades: extremely stable, stable, relatively stable, unstable and extremely unstable, and are assigned to 5, 4, 3, 2 and 1 respectively (see Table 15).

Table 15 Index grades for stability of beach nourishment

Number	Evaluation index	Description	Index grades				
			5	4	3	2	1
1	Wave condition	Significant wave height (m)	⩽ 0.3	(0.3,0.6]	(0.6,0.9]	(0.9,1.2]	>1.2
2	Storm intensity	Historical recorded largest wave height (m)	⩽ 5.0	(5.0,6.0]	(6.0,7.0]	(7.0,9.0]	>8.0
3	Storm frequency	Annual-averaged number of storms (times/ yr)	⩽ 0.5	(0.5,1.0]	(1.0,1.5]	(1.5,2.0]	>2.0
4	Nourishment length	Length in longshore direction (km)	⩾ 2.0	[1.5,2.0)	[1.0,1.5)	[0.5,1.0)	<0.5
5	Nourishment sand grain size	Ratio of mean grain size between nourishment sands and original beach sands	⩾ 1.75	[1.5,1.75)	[1.25,1.5)	[1.0,1.25)	<1.0
6	Sands supply per unit width	Sands supply per unit width on the beach (m3/m)	⩾ 400	[300,400)	[200,300)	[100,200)	<100
7	Beach layout	Layout	Tombolo	Headland	Salient	Straight	Sandspit
8	Auxiliary structure	Type and relative positions of auxiliary structure	Detached breakwater (S/L<2)	Downstream groin	Detached breakwater (S/L>2)	Midstream groin	None
9	Width of intertidal zone	Horizontal distance from high tide level to low tide level (m)	⩾ 80	[60,80)	[40,60)	[20,40)	<20

Number	Evaluation index	Description	Index grades				
			5	4	3	2	1
10	Width of dry beach	Distance from berm frontier to backshore dune or seawall (m)	⩾ 80	[60,80)	[40,60)	[20,40)	<20
11	Erosion hotspot density	Number of erosion hotspot on per unit width of beach (/km)	0	(0,1.0]	(1.0,2.0]	(2.0,3.0]	>3.0

10.2.3.2 Evaluation methods

The weights of the indexes are shown in Table 16.

Table 16 The weights of the evaluation indexes for beach nourishment stability

Evaluation index	Weight
Wave intensity	0.093
Storm intensity	0.050
Storm frequency	0.094
Nourishment length	0.082
Relative grain size	0.126
Sands supply per unit width	0.104
Beach layout	0.045
Auxiliary structure	0.066
Width of intertidal zone	0.119
Width of dry beach	0.086
Erosion hotspot density	0.135

The weighted sum method was used to evaluate the stability of beach nourishment. According to the classification method of the indexes in Table 13, the score of each index is determined. Combined the corresponding weights of each index in Table 14, the Nourished Beach Stability Index, (NBSI) is calculated by the weighted sum method. The calculation formula is as follows:

$$NBSI = \sum_{i=1}^{m}\left(P_i \times \omega_i\right)$$

in which,

m -- number of evaluation index;

P_i -- score of each index;

ω_i -- corresponding weight.

10.2.3.3 Evaluation results

Evaluation results for sandy beach stability can be divided into five grades (see Table 17 for details).

Table 17 Five grades of sandy beach stability evaluation results

Grades	Extremely low	Relatively low	Medium	Relatively high	Extremely high
Description	Extremely unstable	Unstable	Relatively stable	Stable	Extremely stable
Classification (NBSI)	⩾ 1~<2.41	⩾ 2.41~<2.92	⩾ 2.92~<3.08	⩾ 3.08~<3.59	⩾ 3.59~<5

10.2.4 Evaluation of ecological effect

10.2.4.1 Evaluation index

The status evaluation of sandy coastal ecosystem is carried out quantitatively from three aspects: beach characteristics, biocoenosis and environmental elements. See Table 18 for the specific evaluation indexes and assignment weights.

Table 18 Evaluation index and weight assignment of sandy coast ecological condition

Evaluation contents		Evaluation indexes	Index weight
Beach characteristics	Endowment of beach resources	Width of dry beach	40
		Width of intertidal zone	
		Slope of intertidal zone	
		Sediment type	
		Sediment sorting	
		Beach morphology features	
	Disaster mitigation ability	The length of the coastline	40
		Seaward open degree	
		Relative tide range	
		Coastal erosion intensity	
Biocoenosis	Intertidal benthic organisms	Biomass change rate	10
	Backshore vegetation	Rate of total zonal change	
		Rate of coverage change	
Environmental elements	The water environment	Degree of Nearshore seawater quality	10
	Sediment environment	Quality grade of intertidal sediments	

10.2.4.2 Reference systems

Reference system is selected and used in the following ways:

a) Collect historical data of the survey zone, including ecosystem data obtained from routine monitoring, special survey, and literature, and establish a reference system.

b) Reference systems shall adopt data that are representative and reflect changes in the ecosystem.

c) When the entire historical data are available, the historical data shall be used as the reference frame for evaluation.

d) When there is a part of historical data available, some historical data will be used as the reference frame for evaluation, and the missing part of the data will only carry out a descriptive evaluation of the current situation.

e) In the absence of historical data, ecosystem status evaluation shall be carried out only, and the results shall be used as a reference frame for future evaluation.

10.2.4.3 Evaluation methods and results

The ecological evaluation method of sandy coast is shown in the following formula:

$$I_{sc}=S_r+S_d+B+E$$

Where:

I_{sc} -- Comprehensive index of the status of sandy coastal ecosystems;

S_r -- Index of beach resource endowment;

S_d -- Index of disaster mitigation ability;

B -- Biocenosis condition index;

E -- Environmental status index.

The detailed calculation methods of S_r, S_d, B and E can be seen in Section 7.3 of the "Technical guideline for investigation and assessment of coastal ecosystem—Part 8: Sandy Coast". When Isc > 64, sandy coast ecosystem status is stable, which is classified into class Ⅰ; When 30 < I_{sc} ≤ 64, sandy coast ecosystem status is damaged, evaluation level for Ⅱ; When I_{sc} ≤ 30, sandy coast ecosystem status is severely damaged, evaluation level for III .

In the survey results report, the internal causes and external drivers of the changes in the ecological status of sandy coasts are comprehensively analyzed and corresponding management measures are proposed based on the results of the comprehensive evaluation of the ecological status of sandy coasts and the threat factors that are not included in the quantitative evaluation above.

Table 19 Classification and management measures of sandy coastal ecosystem status evaluation results

Classification	Classification description	Management measures
I	The sandy coastal ecosystem is stable, the beach profile topography and layout are in a state of dynamic equilibrium, and the biocenosis, water environment and sedimentary environment are good and self-sustaining	Continuous follow-up monitoring and scientific management
II	The sandy coastal ecosystem is damaged, coastal erosion occurs, and the biocenosis, water environment and sedimentary environment are damaged, which can maintain the basic structure and self-recovery ability	Strengthen ecological management, control threat factors, promote the natural rehabilitation of sandy coastal ecosystems
III	The sandy coastal ecosystem is severely damaged, the coastal erosion is serious, the biocenosis, the water environment and the sedimentary environment are seriously damaged, and it is difficult to maintain the basic characteristics and self-recovery capacity of the beach	Ecological management shall be strengthened to control the threat factors, and artificial rehabilitation measures shall be taken to improve the ecosystem status

10.3 Socioeconomic Benefits of Sandy Coast Restoration

The socioeconomic benefits of sandy coast restoration are evident in several aspects: tourism and leisure benefits, nearshore wealth appreciation, social benefits, and hazard prevention and mitigation benefits. The decision to proceed with sandy coast restoration largely depends on the ratio of economic benefits to maintenance costs over a specific period. The cost–benefit ratio has become the key economic consideration for sandy coast restoration, and comprehensive evaluation of restoration projects and the interrelationships between different costs and benefits should be considered. The assessment of the economic benefits of sandy coast restoration can appropriately draw upon the methodologies employed in evaluating the economic value of beaches[13].

10.3.1 Sandy Coast Restoration Costs

The costs of sandy coast restoration include engineering survey costs, research and design costs, identification and extraction of sand sources, transportation costs (or costs of purchasing and transporting sand), construction costs, and maintenance costs. Assuming that the natural evolution process of a sandy coast restoration project is known, the greatest uncertainty in predicting future renourishment costs lies in the changes that may occur in exploration, extraction, and transportation costs due to changes in the sand source area. Additionally, increased environmental concerns and constraints in the future may increase renourishment costs, leading to increased research costs.

10.3.2 Tourism and Leisure Benefits

Sandy coast restoration expands coastal recreational spaces and enhances the coastal environment, attracting more tourists and generating greater tourism and leisure benefits. As the width of the beach increases, so does its usage, resulting in a growth trend in economic benefits from tourism (Figure 18).

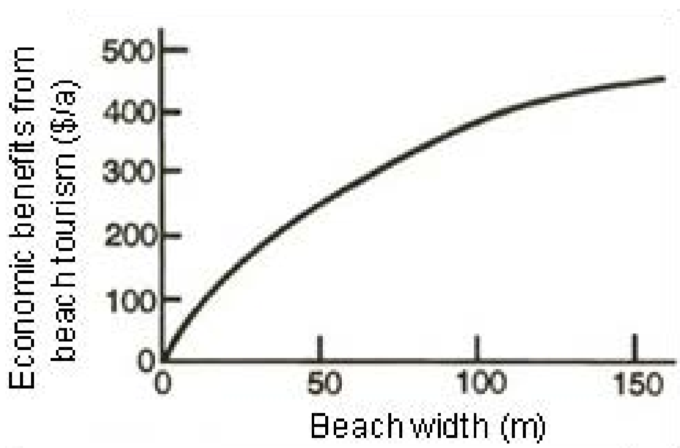


Figure18. Relationship between beach tourism benefits and beach width[14](Source: Dean, 1988)

The implementation of sandy coast restoration in Xiamen has led to the creation of more than 20 kilometres of continuous golden sandy beach coastline around the island. This initiative has systematically improved the environmental quality of the coastline along Xiamen Island Road. As a result, it has become a new focal point for Xiamen's tourism economy, serving as a hub for various beach activities and a popular leisure destination. The impact of this restoration project on Xiamen's tourism industry has been significant. According to the Xiamen Municipal Bureau of Ocean and Fisheries, the beach restoration project in Xiamen has increased the added value of the marine economy created by each square kilometre of offshore water to 100 million yuan, which is 40 times the national average.

10.3.3 Nearshore Wealth Appreciation

Successful sandy coast restoration not only attracts tourists and enhances the environment but also increases the value of nearby coastal land properties. Hence, it brings about nearshore wealth appreciation benefits. Studies on the economic benefits of numerous sandy coast restoration projects conducted by Stronge[15-16] revealed that the natural growth in economic entities, such as real estate and land, in nearshore areas can be attributed to beach maintenance and restoration. For instance, the Marco Island beach restoration project in Florida, with an investment of $4 million, resulted in a 4.5% increase in the value of land properties in restored areas compared to adjacent unrestored areas. This increase amounted to approximately $9 million and generated $132,000 in tax revenue[15]. The Captiva Island beach restoration project in Florida increased property values by 20.6%, resulting in $200 million in property appreciation and an additional $1 million in property taxes.

By capitalizing on sandy coast restoration at Guanyinshan, Xiamen has successfully developed a high-quality "Dream Coast" tourism and business district. The Guanyinshan International Business Operations Center has become a regional hub that integrates research and development, operations, exhibitions, and residential areas. It is estimated that upon completion, the area will generate an annual tax revenue of 2 billion yuan. Since its development began, the area has already generated more than 1 billion yuan in taxes, with 560 million yuan in taxes generated from January to July 2011 alone. Although it is difficult to quantify the indirect wealth appreciation benefits brought about by the restored golden coast, their existence is undeniable.

10.3.4 Social Benefits

Sandy coast restoration projects have a significant impact on coastal cities, serving as central hubs for coastal activities and generating valuable social and cultural effects. One example is the Guanyinshan sandy coast restoration project in Xiamen, which has provided a new platform for various coastal cultural and sports activities, resulting in substantial social benefits. Another notable project is the restoration of Longfengtou Beach in Pingtan, which has transformed into a prominent tourism attraction for Pingtan Island and a key venue for large-scale social gatherings, yielding significant social impact.

The Guanyinshan sandy coast restoration project in Xiamen was completed in 2007 and has since hosted numerous influential coastal cultural and sports activities. These include the Xiamen Guanyinshan Beach Culture Festival, beach soccer and volleyball tournaments. These activities have made significant contributions to enhancing Xiamen's coastal leisure and entertainment offerings and enriching its beach culture. The Xiamen Guanyinshan Beach Culture Festival, which has been held five times since 2008, has been particularly impactful. It has successfully explored the coastal cultural aspects of Xiamen, fostered the growth of the cultural industry, expanded the cultural significance of Xiamen's "Sun, Sand, Sea" concept, and showcased the coastal city's charm to both domestic and international tourists. Furthermore, it has become a new landmark for the city. Guanyinshan Beach has received recognition from the Volleyball Management Center of the General Administration of Sport of China as the "National Beach Volleyball Event Base of the Chinese Volleyball Association," indicating that more major beach volleyball events will be held there in the future. The simultaneous hosting of the National Beach Volleyball Championship and the Cross-Strait Beach Volleyball Invitational Tournament, which invited university teams from Taipei and Taichung, promoted sports exchanges between universities on both sides of the Taiwan Strait and built a new bridge for cross-strait cultural exchange.

Longfengtou Beach, located on Pingtan Island, used to be a popular summer destination for the residents of Pingtan and the surrounding areas. Unfortunately, in the 1990s, the construction of sea walls severely damaged the beach. However, in July 2011, a sandy coast restoration project took place, revitalizing the beach and making it a popular tourist spot once again. This restoration project led to the hosting of various important beach activities, including the "Cross-Strait (Pingtan) Beach Culture Festival," which opened on June 17, 2012, and lasted three months. The festival attracted many tourists and greatly promoted tourism in Pingtan. Additionally, in May 2012, the "Kiteboarding Tour Asia (KTA) China Pingtan Stop" was held at Longfengtou Beach, further connecting the Pingtan Comprehensive Experimental Zone with the world and injecting fresh energy into the development of Pingtan as an internationally renowned island tourism destination and a modern, international comprehensive experimental zone.

10.3.5 Hazard Prevention and Mitigation Benefits

This sandy coast restoration project has not only enhanced the stability of the beach but also created a complete and stable beach geomorphological system that serves as an optimal buffer for coastal hazard prevention and mitigation. This approach significantly improves the ability to withstand storm surge hazards, thereby enhancing overall coastal protection. The restoration of beaches in artificial coastal areas has shifted the focus from rigid to soft protection, creating a buffer zone between the sea and the land. This buffer zone dissipates wave energy through dynamic geomorphological adjustments, reducing the destructive power of typhoons and other severe weather conditions and ultimately effectively increasing coastal resilience.

A great example of the success of sandy coast restoration projects is in Zhuhai, where the restored beach withstood the direct impacts of two super typhoons, "Hato" and "Mangkhut," effectively protecting against storm surge hazards and acting as a natural barrier for coastal defence in Zhuhai. During these typhoons, the restored beach at Xianglu Bay effectively protected the road and other facilities behind it, leaving the coastal guardrail intact. In contrast, the adjacent sections without beach protection experienced more than ten seawall collapses and nearly one hundred damaged coastal guardrails. Figure 19 shows the protected beach at Xianglu Bay, while Figure 20 illustrates the damage in adjacent sections without beach protection.

Figure 19. The coastal guardrail and backshore facilities protected by the restored beach remained intact during the super typhoon

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

Figure 20. Coastal section without beach protection showing a collapsed seawall and damaged

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

10.4 Adaptive Management after Restoration

Based on the monitoring and effectiveness evaluation results following the restoration of sandy coasts, the issues encountered during the restoration process need to be analyzed. These include issues related to beach morphology, environmental quality, and ecological habitat. Different management measures will be implemented to address these specific issues.

(1) Maintenance of beach morphology

The nourished beach may be susceptible to erosion due to various factors, including waves, currents, and surface runoff from heavy rainfall, which can result in the degradation of beach morphology. The extent and severity of this degradation can inform whether the necessary maintenance is internal adjustments or if external sand sources are required for maintenance. Internal adjustments within the beach system, such as redistribution of sand between the upper and lower intertidal zones, or between upstream and downstream segments in the sand transport direction, are considered routine maintenance of beach morphology. However, if erosion is sufficiently severe to jeopardize the overall stability and functional use of the beach, external sand input will be necessary to uphold coastline stability. According to the "Technical Guide for Beach Nourishment and Restoration" (HY/Y 255-2018), renourishment efforts should be conducted when sediment loss exceeds 50%.

(2) Maintenance of beach environmental quality

The issue of waste generated from river input or coastal activities necessitates regular and dedicated cleaning and maintenance efforts. Additionally, it is essential to adhere to municipal management requirements for the collection, packaging, and transportation of beach litter. Beach cleaning efforts should be conducted daily to ensure the cleanliness of the coastline.

Due to natural or anthropogenic factors, issues such as the armoring of backshore, the accumulation of biological debris, and a decrease in beach comfort may emerge. To address these problems, periodic mechanical and manual cleaning and maintenance are necessary. Utilizing beach vehicles equipped with plowing and raking functions to regularly till the backshore can help maintain loose sand and enhance visitor comfort. It is recommended that this maintenance be performed approximately once every month, although the frequency may be adjusted based on the specific conditions of the beach. To mitigate the accumulation of biological debris on the backshore, a method involving periodic screening of a certain thickness of sand from the surface is suggested, ideally once or twice a year, with the exact timing determined according to the local beach conditions.

(3) Maintenance of beach ecological habitat

To address the accumulation of aeolian sands on backshore pathways such as boardwalks and greenways, it is advisable to implement measures such as installing sand fences or replanting coastal vegetation. Regular sand removal should be conducted based on the extent of accumulation caused by strong winds, typically completed within 1~2 days following such weather events. In response to issues related to the absence, damage, or degradation of coastal vegetation behind the beach, it is essential to enhance the maintenance and management of backshore vegetation, in accordance with relevant regulations for urban green space management.

11.Classic Cases of Sandy Coast Restoration

11.1 Case 1—Jinwu to Qianshui Bay, Qinhuangdao, China

Ⅰ. Project Overview

Qinhuangdao is located in the northeastern part of Hebei Province, bordering the Bohai Sea to the south and backed by the Yanshan Mountains to the north. It is recognized as one of China's top ten eco—civilized cities, the most liveable city in northern China, and one of the most beautiful coastal cities in China. The soft, gently sloping sandy beaches, clear waters, and picturesque scenery make Qinhuangdao's beaches a significant draw for both domestic and international visitors. However, continuous wave action has led to the gradual erosion of sand, resulting in the decay of the dry beach area along from Jinwu to Qianshui Bay. Waves have damaged the seaside wooden boardwalk and pose a serious threat to the road along the coast.

The beach in the Jinwu to Qianshui Bay section has been in a state of erosion for a long time, with increasing severity under the influence of storm surges. Before restoration, the beach had eroded up to the coastal boundary markers, with most of the beach berms having disappeared, and parts of the vegetated dunes had eroded. The wooden boardwalk collapsed, and the beach's ecological functions and tourism and recreational value declined significantly.

Figure 21. Coastal landscape of Jinwu to Qianshui bay before restoration

(Source: Hebei Center of Marine Geological Resources Survey)

In 2018, the Qinhuangdao Municipal People's Government commissioned the 8th Geological Brigade of the Hebei Provincial Geological and Mineral Exploration and Development Bureau as the technical support unit to carry out the application work of the Bohai Comprehensive Management Action Plan. The beach restoration project for the eroded section from Jinwu to Qianshui Bay was included in the 2018 Bohai Comprehensive Management Action Plan. The project respected, conformed to, and protected nature. Through marine geological surveys, the topography, geomorphology, marine dynamics, and marine environment characteristics of the project area were identified, and the causes of shoreline erosion were clarified. Multiple protective measures were implemented, including beach berm nourishment, artificial dunes, underwater sandbars, offshore submerged breakwaters, and sand dikes, to create a stable beach shoreline. After the project's completion, it successfully withstood the impacts of several storm surges, including Typhoon Lekima, demonstrating excellent protective effects and significantly enhancing the area's hazard prevention and mitigation capabilities.

Ⅱ. Natural Geographic Conditions of the Project Area

(1) Climate and Meteorology

Qinhuangdao city has a temperate semihumid continental monsoon climate characterized by four distinct seasons. Due to the significant influence of the ocean, the climate is relatively mild. The spring is dry with little rain, the summer is warm without extreme heat, the autumn is cool with many sunny days, and the winter is long without severe cold.

Sunshine: The annual average sunshine duration in Qinhuangdao is between 2700 and 2850 hours.

Temperature: The annual average temperature ranges from 8.8 to 11.3° C, and the average daily temperature in midsummer ranges from 22 to 25° C.

Precipitation: The annual average precipitation is between 650 and 750 mm and is mostly concentrated in the summer, with little precipitation occurring in the winter.

(2) Marine Hydrology

Tides: The sea area experiences regular semidiurnal tides with an average tidal range of 0.7 m. The average tidal level is lower in winter and higher in summer, with significant fluctuations. The average tidal level is lowest in December at 62 cm and highest in July and August at 114 cm.

Waves: The waves in the Qinhuangdao sea area are primarily wind waves, with some secondary swells, and wave formation mainly depends on the wind direction. The average wave height is between 0.4 and 0.6 m, with a maximum wave height of 3.5 m. The average wave period is 2.6 seconds.

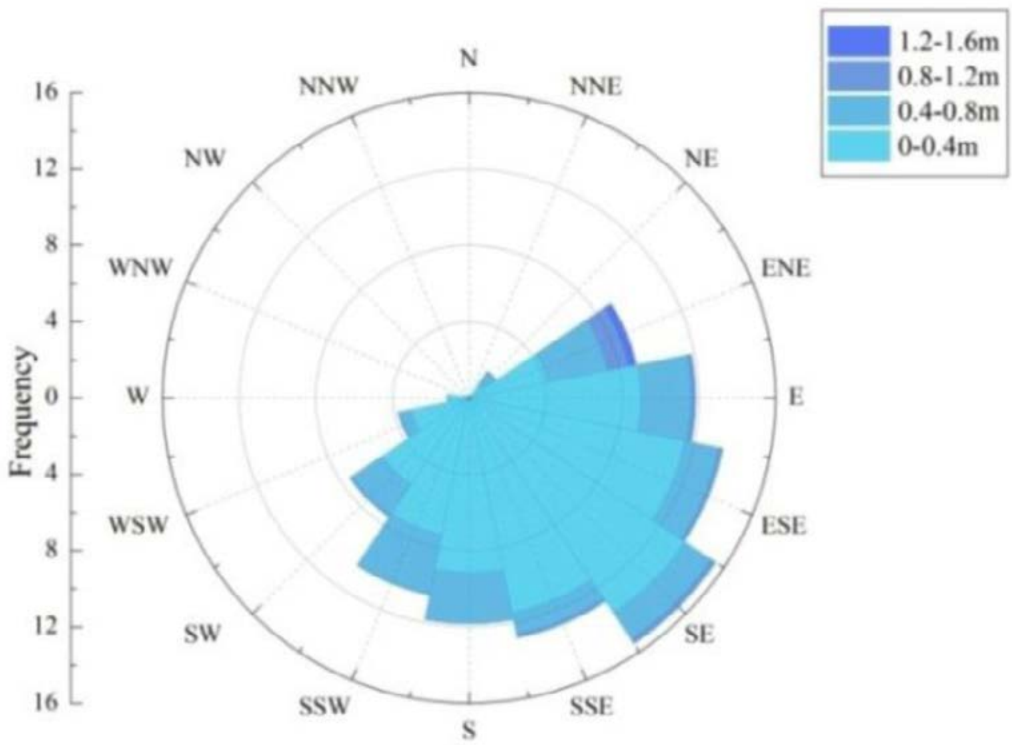


Figure 22. Wave rose of restoration area

(Source: Hebei Center of Marine Geological Resources Survey)

Ⅲ . Beach Restoration Plan

Restoration Approach: Respect natural space to achieve harmony between humans and nature, ensure ecological diversity for coexistence between humans and the ecosystem, integrate the landscape environment to share natural scenery, and create a waterfront leisure environment to promote harmony among people.

(1) Beach Berm Nourishment

Beach berm nourishment can quickly increase the width of the dry beach. Using an intersecting profile, the length of the restored beach is 3.5 km. After restoration, the beach elevation reached 2.0 m, and the beach width increased from 20 to 60 m.

(2) Artificial Dunes

Dunes are common geomorphic features in coastal areas and serve as the last line of defence in coastal natural defence systems due to their unique location and composition. In recent years, artificial dunes have been reconstructed to restore the natural environment and protect the coast. Nearshore areas from Jinwu to Qianshui Bay have vegetated dunes, but most dunes have been eroded, resulting in reduced dune width and deteriorating vegetation. Based on the morphology of the surrounding native

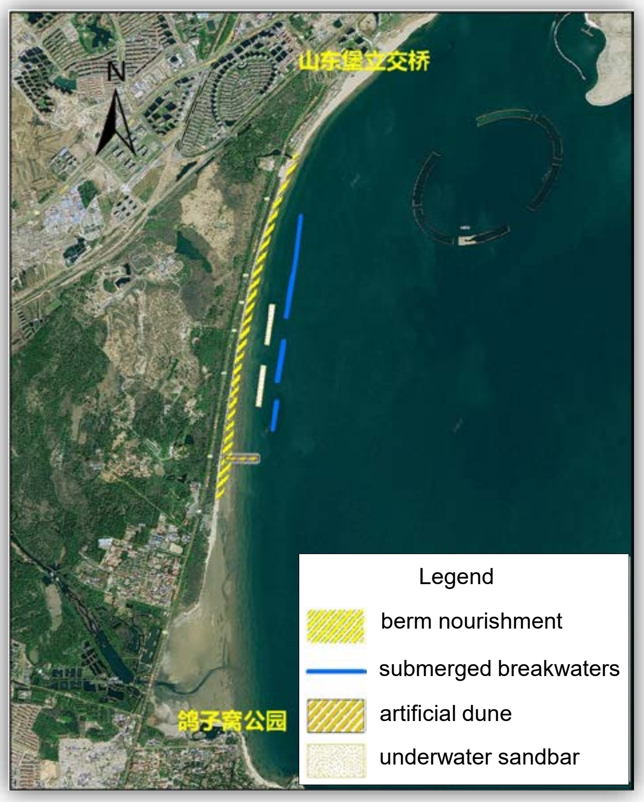


Figure 23. Layout design of sandy coast restoration

(Source: Hebei Center of Marine Geological Resources Survey)

vegetated dunes, artificial dunes were created at the back of the nourished beach berm. The artificial dunes extend 3.5 km, with an elevation of 3.0 m and a width of 10 m.

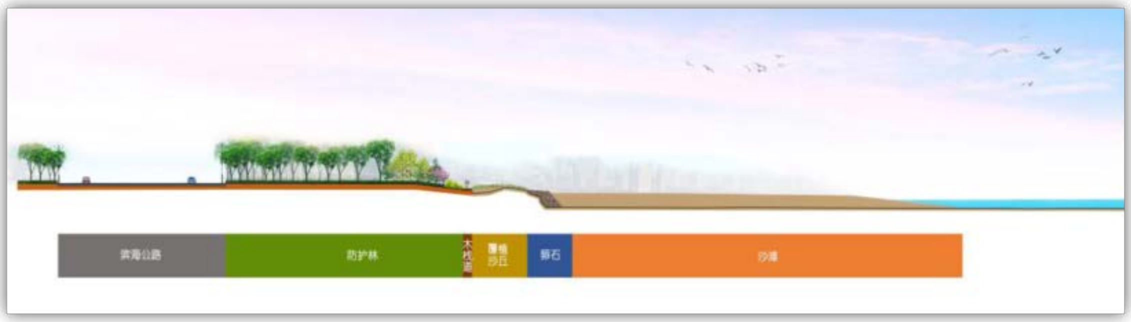


Figure 24. Restoration profile (Source: Hebei Center of Marine Geological Resources Survey)

(3) Underwater Sandbars

Underwater sandbars are narrow, elongated depositional features parallel to the coast but not exposed above the sea surface. Sandbars were constructed using medium to coarse sand relatively close to the shore to provide nourishment and shielding effects. The nourishment effect refers to the transport of sand from the nearshore sandbar to the beach under wave action, leading to sediment deposition at a certain location behind the bar. The shielding effect occurs as waves break over the sandbar, dissipating wave energy towards the beach and reducing sediment transport in the sheltered area, thereby protecting the coast. This project involved designing two underwater sandbars, approximately 200 m offshore, with a total length of 800 m, a crest width of approximately 50 m, and a crest elevation of 0.0 m.

Figure 25. Layout of underwater sandbars (Source: Hebei Center of Marine Geological Resources Survey)

(4) Offshore Submerged Breakwaters

The aim of building offshore submerged breakwaters is to reduce wave energy by causing waves to break earlier, thereby reducing beach erosion and promoting the development of a balanced shoreline. This project used fish reef–type submerged breakwaters, which have a low impact on water circulation and the ecological environment. The crests of the breakwaters are submerged, preserving the visual landscape. The project includes a total of three submerged breakwaters with a combined length of 1650 meters.

(5) Groins

Groins are designed to create a headland – bay shape and reduce alongshore currents. One groin with a length of 400 meters, a crest width of 50 meters, and a crest elevation of +0.5 meters is planned for this project.

Ⅳ. Coastal Restoration Effects

By utilizing an expanded and optimized beach ecological restoration model, the beach width has increased by 20 to 60 meters. The multilayered protection system overcomes issues associated with traditional artificial beach nourishment methods, such as a short lifespan, loss of beach self–sustenance, and conflicts between nourishment projects and habitat protection. This approach has been applied in various coastal ecological restoration projects in Qinhuangdao city. The project's implementation has effectively reduced coastal erosion and retreat, restored damaged beach resources and coastal ecological environments, enhanced the ecological and tourism value of the beach, and improved the coastal capacity to withstand erosion.

Figure 26. Coastal landscape before and after restoration

(Source: Hebei Center of Marine Geological Resources Survey)

11.2 Case 2—Xianglu Bay, Zhuhai, China

Ⅰ. Project Overview

Zhuhai is considered the most liveable city in China, with a suitable climate, beautiful environment, and abundant coastal tourism resources. Lovers' Road is the most scenic coastal section in Zhuhai, passing through famous tourist spots such as Jiuzhou Port, the Seaside Swimming Pool, Zhuhai Fisher Girl, and Xianglu Bay. The continuous sound of waves and picturesque scenery make Lovers' Road one of the city's urban landmarks. However, for various reasons, except for a few hundred metres of sandy beach at the seaside bathing area, other sections of Lovers' Road have little to no beach, significantly reducing the coastal leisure and tourism space and not matching Zhuhai's status as a coastal tourism city.

Xianglu Bay is located in the middle section of Lovers' Road. Before beach restoration, small patches of sandy beaches were dispersed along the bay, each a few metres to several tens of metres long, with a relatively small overall scale and no dry beach exposed at high tide. The beach surface had a distinct slope break, with the high to mid-tide zone above the slope break being 10–30 m wide and composed of loose grey-yellow coarse sand with a steep slope. Towards the low-tide zone, the slope became gentler, and the sediment gradually transitioned to silty mud or muddy silt, with surface mud and many pebbles.

Figure 27. Coastal landscape of Xianglu bay before restoration

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

In 2014, the Zhuhai Municipal People's Government commissioned the Third Institute of Oceanography, Ministry of Natural Resources, to design a beach restoration and improvement plan for the Lovers' Road coastal section. The plan was based on the beach location, and the beach berm nourishment restoration method was designed according to the measured topography and hydrodynamic environment of the sea area. The plan involved the reasonable use of natural headlands and the construction of groins to create a stable headland – bay shoreline. The shoreline restoration further expanded the coastal tourism and leisure space along the Lovers' Road in Zhuhai, achieving significant social and economic benefits.

Ⅱ. Natural Geographic Conditions

(1) Climate and Meteorology

Zhuhai is located south of the Tropic of Cancer and is characterized by notable alternation between winter and summer monsoons. The annual temperature is relatively high, with mild winters and moderately warm summers, and the diurnal temperature variation is small. The climate is classified as subtropical maritime.

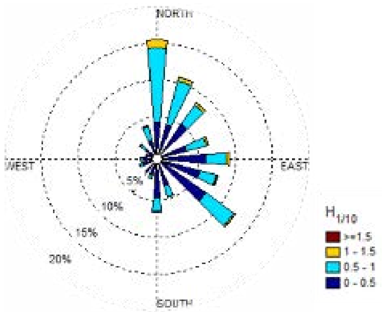
Temperature: The annual average temperature is 22.3℃, with a lowest recorded temperature of 2.5℃. Spring weather is variable with significant temperature fluctuations. The average monthly temperature in summer is 28.6℃, with a maximum temperature of 38.5℃. Winter temperatures are lower, with January being the coldest month, averaging 14.5℃.

Precipitation: Zhuhai receives abundant rainfall, with an annual average precipitation ranging from 1770 to 2300 mm. The rainy season occurs from April to September, dominated by southeast monsoons, accounting for 85% of the annual precipitation; the dry season occurs from October to March, dominated by northeast monsoons.

Wind conditions: The average annual wind speed is 3.1 m/s, with significant seasonal variations in the wind direction. Southerly and southwesterly winds prevail in summer, often bringing typhoons; northerly and northeasterly winds are most frequent in autumn and winter, with southeasterly and northeasterly winds prevailing throughout the year. The number of strong wind days (wind speed > 17.2 m/s) varies significantly by region, with an annual average of 9.2 days in the Xiangzhou area.

（2）Marine Hydrology

Tides: The tides in this sea area are classified as the irregular semidiurnal mixed type, with a relatively small tidal range, making it a weak tidal zone. The tidal currents exhibit reciprocating flow.



Waves: In winter, the predominant waves are from the north, accounting for 27%, followed by those from the NNE. In summer, the common wave direction is from the southeast, with a frequency of 13%, followed by waves from the south, with a frequency of 11%. The significant wave heights are mostly below 1.0 m. The dominant wave directions throughout the year range from north to southeast.

(3) Topography and Geomorphology

The Xianglu Bay coastal section includes two types of landforms: low hills and plains. Half of the coastline lies in a low hilly area, characterized as a mountainous bay coastline, while the other half is situated in a coastal plain area, classified as a plain coastline. The entire bay section was reinforced with vertical artificial seawalls. Due to the weak hydrodynamic forces within the bay, the coastal geomorphology primarily exhibits a mixture of sandy beach and muddy tidal flat.

Ⅲ . Beach Restoration Plan

Project Positioning: This project is positioned as a tourism, leisure, and sports–oriented coastal restoration project with landscape beautification functions. The goal is to restore and expand the existing beach through sand nourishment, creating a coastal sandy shoreline with complete geomorphological units.

Restoration Approach: Based on the project positioning, the design includes beach berm nourishment, the reasonable use of natural headlands and the incorporation of appropriate sand stabilization structures to create a stable headland – bay shoreline and to form a broader dry beach space.

(1) Profile Design

Considering the need to quickly increase coastal leisure space, the beach berm nourishment restoration method was adopted.

Beach Berm Width: The designed average width of the constructed beach berm is approximately 75 metres. After restoration, the beach will naturally adjust under hydrodynamic forces, with the dry beach width gradually decreasing and stabilizing. The expected stable average berm width is approximately 50 metres.

Beach Berm Elevation: The designed berm elevation is 0.5 metres lower than the road along the coast, allowing for localized overwash during high tides and storms. At this stage, the berm elevation is determined with reference to the "Technical Guide for Beach Nourishment and Restoration" (HY/Y 255–2018) and the elevation of the backshore infrastructure.

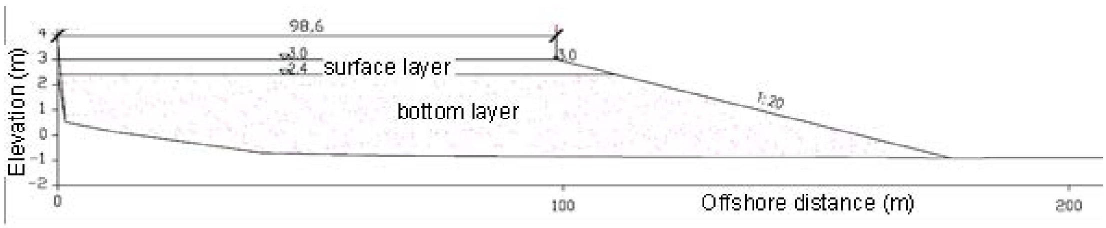


Figure 28. Profile design of beach nourishment for Xianglu bay

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

(2) Sand Replenishment Design

The beach replenishment will use medium–fine to medium sand with a grain size of 0.3 to 0.6 mm. A layered design will be adopted, with higher quality sand for the surface layer and a subsurface sand layer with a slightly larger grain size and sorting compared to the designed sediment grain size. A total of 372,000 cubic metres of sand will be added, including 75,000 cubic metres of surface sand and 297,000 cubic metres of subsurface sand.

(3) Layout Design

The Xianglu Bay coastal section has Ye Li Island to the north and a natural headland at Seaside Park to the south, providing an initial natural headland – bay shape. Based on the existing coastal morphology, sand trapping groins will be constructed on the north and south sides of the beach restoration area to create a more stable and balanced headland – bay shoreline.

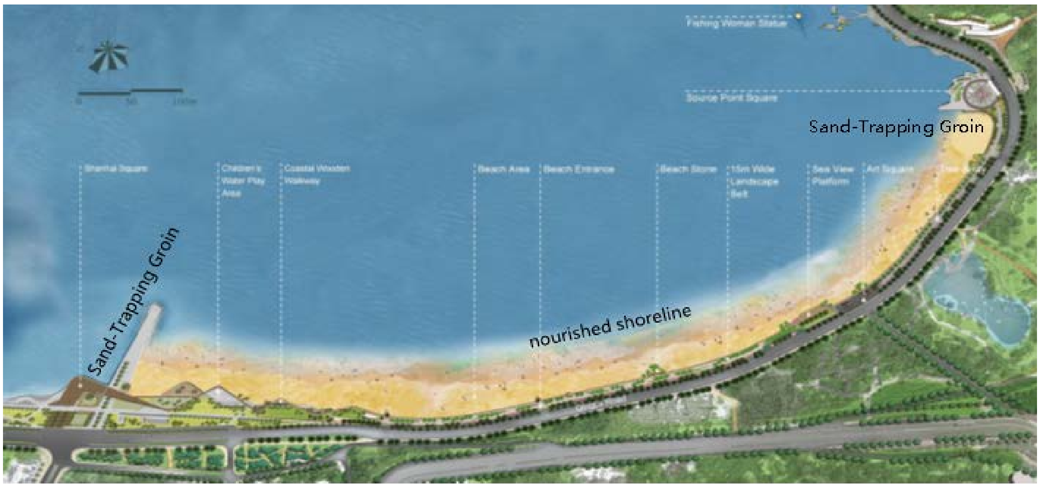


Figure 29. Layout design of beach nourishment for Xianglu bay
(Source: Third Institute of Oceanography, Ministry of Natural Resources)

(4) Auxiliary Structure Design

North Sand–Trapping Groin: This structure has a length of 360 m, a crest elevation of 3.80 m, and a crest width of 6.00 m.

South Sand-Trapping Groin: This structure has a length of 100 metres, a crest elevation of 3.50 metres, and a crest width of 3.00 metres.

(5) Backshore Vegetation Design

Plant Selection: Wind-resistant, salt-tolerant plants that also provide landscape benefits should be selected based on the dynamic coastal environment of the project area.

Layered Structure: A combination of trees, shrubs, and grasses should be implemented to create a rich and layered plant community that integrates with the surrounding landscape elements.

Figure 30. Backshore vegetation restoration for Xianglu bay
(Source: Third Institute of Oceanography, Ministry of Natural Resources)

Ⅳ. Coastal Restoration Effects

The implementation of the Xianglu Bay coastal restoration project in Zhuhai holds significant practical importance for expanding the coastal tourism space along Lovers' Road, protecting the coastline, and promoting the "Beautiful Zhuhai" initiative.

The project has significantly boosted the local tourism economy in the Xiangzhou District of Zhuhai, promoting land value appreciation along the route and the development of tertiary industry, yielding indirect economic benefits. The project has provided valuable waterfront space for Zhuhai residents and tourists, attracting millions of visitors annually and qualitatively enhancing the core space of Zhuhai's "One Belt, Nine Bays." This has led to remarkable social benefits. The Xianglu Bay restoration project has become a model for coastal ecological restoration, gaining recognition both domestically and internationally, and has been awarded the "IFLA Award of Excellence," "Dame Sylvia Crowe Award-LI, UK Royal," and the "China Habitat Environment Model Award."

Figure 31. Coastal landscape before and after restoration, and the award of restoration project for Xianglu bay

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

Appendix: Knowledge of Sandy Coasts

1. Concept and Definition of Sandy Coasts

(1) Definition of the Coastal Zone and Shoreline

The coastal zone refers to the area where land and sea interact, encompassing the upper limits of seawater influence on the coast, the adjacent land, the intertidal zone, and the area affected by the sedimentation and erosion of the seabed slope below the tidal zone due to seawater movement. The definition of coastal zone width varies by country. According to the "National Survey of Coastal Zones and Tidal Flat Resources Comprehensive Guidelines" in China, the coastal zone generally extends approximately 10 km inland from the shoreline and expands seaward to the 10-15 m isobath. In estuarine areas, it extends inland to the boundary of the tidal zone and seaward to the edge of the freshwater plume. Figure 32 illustrates a typical coastal zone profile including sandy beaches and the distribution of various geomorphic types within its subdivisions.

The shoreline, also known as the indicative coastline, is not a physical line but a conceptual representation of the land-sea boundary. According to the "National Basic Scale Map Symbols Part 1: 1:500 1:1000 1:2000 Topographic Map Symbols" (GB/T 20257.1—2017), the shoreline is defined as the water-land boundary at the average high tide during spring tides; the drying line is the water-land boundary at the lowest low tide (lowest low tide line). The shoreline usually corresponds to natural geographic features such as cliffs, water edges in tidal-influenced estuaries, the outer edge of dune slopes, and the boundary where terrestrial vegetation can no longer survive on the sea-facing side of the backshore (as shown at the outer edge of the backshore terrace in Figure 32).

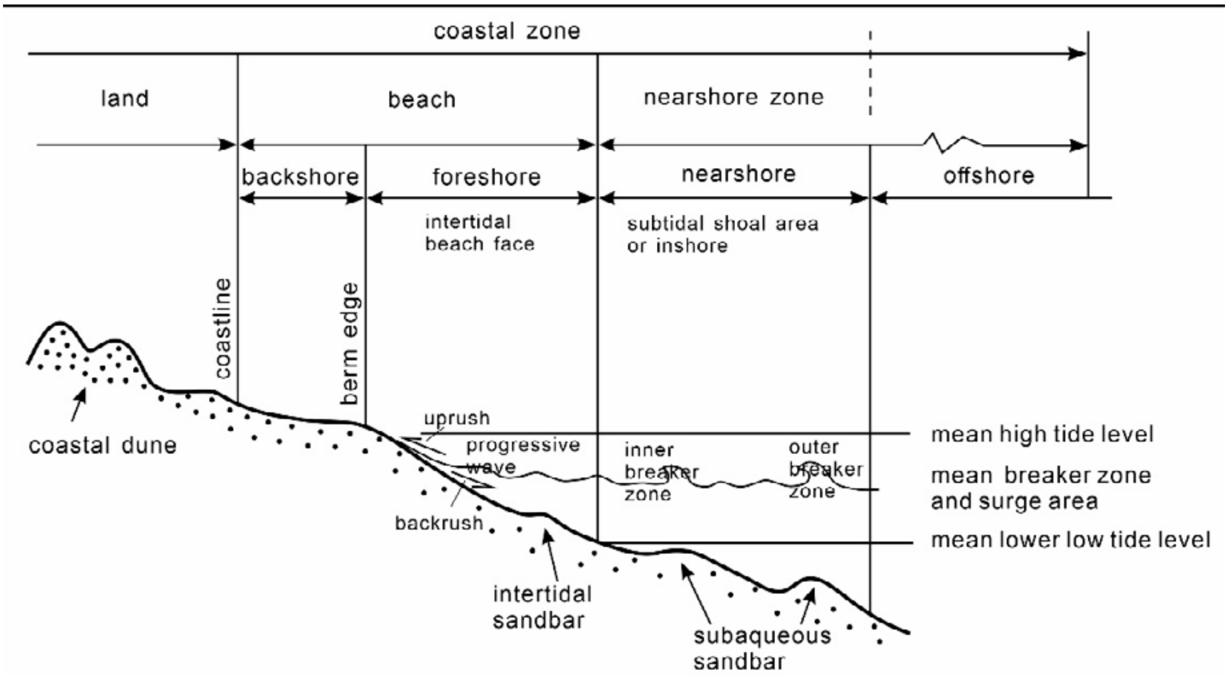


Figure 32. Geomorphic Classification and Related Terminology of Coastal Zone Profiles (Examples of Sandy Coasts) [18] (Source: Cai et al., 2019)

(2) Classification of coastal geomorphology

The zone where the ocean and land interact is composed of three parts: the supratidal zone, the intertidal zone, and the subtidal zone (underwater shore slope). The intertidal zone lies between the high and low tidal marks of spring tides and is submerged or exposed due to tidal fluctuations. It essentially corresponds to the coastal zone's main geomorphic units, which are shaped by tides and waves, forming tidal flats, beaches, rocky shores, mangrove swamps, and coral reefs.

① Muddy Coast

A muddy coast is composed of silt and mud particles smaller than 0.05 mm. This type of coast features relatively straight shorelines, wide beaches, and very gentle slopes. Tidal currents play a dominant role in shaping these slopes. As tidal waves enter shallow waters, the wave front steepens, and the flood current velocity exceeds the ebb current velocity, leading to strong sediment lifting and high sediment-carrying capacity, creating a turbid layer on the seabed. During flood tides, bottom sediments are pushed towards the shore, causing the beach to continuously prograde and resulting in a very gentle slope, typically ranging from 0.5‰ to 1‰ .

② Sandy Coast

The intertidal zone of a sandy coast primarily consists of sand (grain size 0.063 to 2 mm), which makes up more than 75% of the sediment composition, with the remaining clastic particles (gravel or silty mud particles) comprising less than 25%. When gravel or silty mud particles constitute 25 to 50%, the sediments are classified as gravelly sand or silty muddy sand.

Definition of Beach

Beaches are significant geomorphological units of sandy coasts and are formed by the deposition of loose sediments by wave action and swash flows. The definition of a beach varies. According to the US Army Corps of Engineers, a beach is defined as the boundary zone of a sea (including larger bodies of water such as bays, lagoons, and estuaries) — an accumulation of unconsolidated sediments forming a gently sloping coastal area. According to the "Marine Science Terminology (Second Edition)" published by the National Science and Technology Terminology Review Committee, a beach is a sandy or gravelly accumulation formed by wave action in the intertidal zone, gently sloping towards the sea. This handbook defines a beach as the coastal geomorphic unit located between the shoreline and the surf zone, mainly shaped by wave action and composed of unconsolidated sand and gravel sediments. Beaches can be subdivided into the backshore, foreshore, and inshore, with the beach face generally corresponding to the fores hore.

Beaches are mainly distributed along wave-dominated coasts, with well-sorted sediments produced by wave action. The beach surface often features asymmetric ridges (beach ridges) and troughs. Longshore drift and wave refraction can form sand spits[19]. The sediment composition tends to become finer from the shore towards the sea; the high-tide zone is typically coarser and dominated by medium to coarse sand, while the mid- and low-tide zones are finer and consist mainly of medium to fine sand. The geomorphology of beaches is diverse and includes coastal dunes, lagoons, sand spits, and tombolos.

③ Bedrock Coast

Bedrock coasts have jagged and highly curved shorelines, alternating between headlands (protruding landforms) and bays (indentations into the land). These coasts feature various erosional landforms, such as sea cliffs, sea stacks, sea caves, and wave-cut platforms, formed by the differential erosion of softer and harder rocks. Wave-cut platforms typically lie near the mean sea level but can also be found above the high tide line as storm wave platforms or below sea level as wave-cut terraces.

④ Mangrove Coast

Mangroves are evergreen shrub or tree communities composed mainly of mangrove species that grow in the upper intertidal zone of tropical and subtropical low-energy coasts and are periodically flooded by tidal waters. Globally, mangroves are distributed between the Tropic of Cancer and the Tropic of Capricorn, extending up to 32° N and down to 33° S. In China, mangroves belong to the Indo-West Pacific mangrove system, comprising 37 species from 20 genera and 16 families[20] that are naturally distributed in Guangdong, Guangxi, Hainan, Fujian, and Taiwan provinces[21]. The successful introduction of mangroves in Ruian, Zhejiang, in the 1980s extended their distribution northwards to 28° N.

Mangroves typically grow on muddy tidal flats in sheltered bays or river estuaries and are influenced by various factors, such as temperature, ocean currents, waves, slope, salinity, tides, and substrate.

⑤ Coral Reef Coast

Coral reefs are special geomorphological features formed by the skeletal remains of reef-building corals, along with calcareous algae and shell fragments, which accumulate over long periods. These porous calcium carbonate structures develop in shallow waters less than 20 meters deep.

Based on geographical distributions, geomorphological types, geological characteristics, and developmental history, China's coral reef geomorphology can be divided into three major reef areas: a. The South China Sea Islands Area, which includes the Dongsha, Xisha, Zhongsha, and Nansha archipelagos, is characterized by long-term development of atolls since the Tertiary period, with coral reef deposits exceeding a thousand meters in thickness. b. The Northern South China Sea Coastal Area includes the coastal areas of Hainan Island, the Beibu Gulf, the coastal regions of Guangdong, Guangxi, and Fujian, and adjacent small islands. Fringing reefs have formed since the Holocene, with some offshore reefs, lagoonal fringing reefs, and "bottom reefs" now submerged; coral reef deposits are typically thin, usually not exceeding 10 metres. c. The Taiwan Coastal Area includes the eastern coast of Taiwan Island, the Hengchun Peninsula, Tainan, Kaohsiung, the Penghu Islands, the Diaoyu Islands, and other small islands. This area is characterized by uplifted coral reefs that formed since the start of the Quaternary Period, featuring long-term development of fringing reefs.

2. Development and Distribution of Sandy Coasts

The development and distribution of sandy coasts in China have the following characteristics:

(1) Structural Framework Controls the Overall Layout of Sandy Coasts

The formation and development of sandy coasts are influenced by tectonic activity, which creates a pattern for local sediment accumulation under hydrodynamic conditions. The regional tectonic background is fundamental to beach development. China's coastal areas are located in the subduction zone between the Pacific Plate and the Eurasian Plate, where a typical trench – arc – basin system forms a series of marginal seas (including the Yellow Sea, East China Sea, and South China Sea), making it one of the most tectonically active regions on Earth. The frequent volcanic and seismic activity in the Chinese coastal zone has led to the development of a series of faulted basins, uplifted areas, and fold-related mountains. In faulted basins, deltas and ancient coastal plains have developed, forming muddy or sandy coasts with rising sea levels during the Holocene. Sandy beaches are commonly found along sandy coasts. In uplifted and fold-related mountain areas, coastal terraces and mountain fronts meet the sea, and the rise in sea level during the Holocene created a series of drowned valleys and rocky shorelines, with the weaker hydrodynamics within the drowned valleys typically developing muddy shorelines. Under hydrodynamic conditions, rocky shorelines facing open seas form a series of bays of varying sizes where eroded terrestrial materials accumulate to develop beaches. The subduction-related active continental margin characteristics of China's coast have resulted in the development of headland – bay beaches and primary bay lagoon beaches, which differ from the barrier island beaches of the Atlantic coast of the United States. Barrier island coasts are rare in China, reflecting significant regional structural control over the distribution of sandy coasts.

(2) Influence of River Estuaries on Sandy Coast Development

The coast is the centre of the land-sea exchange of energy and material, and the sediment generated by rivers is a dominant factor in coastal development. China has 1,879 river estuaries, with a total catchment area of 4.31 million km^2, and river-borne sediment plays a crucial role in coastal development, significantly influencing the development of sandy coasts. The abundant fine-grained material transported by rivers accumulates in estuaries and nearby areas, forming muddy shorelines and leaving little space for the development of sandy beaches. The high concentration of suspended sediment in Chinese rivers results in large amounts of sediment entering the sea. The Yellow River in northern China has changed its course multiple times, forming both the rapidly growing modern Yellow River Delta and the abandoned Yellow River Delta along the Jiangsu coast, with fine-grained sediment dominating the muddy coasts of Jiangsu and western Bohai Bay, preventing sandy beach development. The sediment carried by the Yangtze River extensively influences the coasts of Shanghai and Zhejiang, leaving little room for sandy beach development in these regions. Additionally, deltas formed by rivers such as the Liao River, Luan River, and Min River have rarely developed sandy beaches. In contrast, the Pearl River has a lesser impact on the surrounding sandy beaches due to high vegetation coverage in its basin, leading to a lower sediment content, and its estuary is a drowned valley, leaving the estuary in a state of sediment "hunger" with most sediment deposited within the estuary, providing more opportunity for surrounding beach development. Overall, the distribution pattern of sandy coasts in China is interspersed among major river estuaries, where fine-grained sediment accumulation in delta regions deprives space and conditions for sandy beach development. The influence of the Yellow and Yangtze Rivers results in few sandy beaches in the central regions of Jiangsu, Shanghai, and northern Zhejiang.

(3) Coastal Erosion and Human Impact on Sandy Coast Development

Global climate change, sea-level rise, and human activities have led to widespread coastal erosion and significant degradation of sandy beaches. Many coastal beaches have disappeared due to sand mining. According to comprehensive survey data of China's 908 coastal zones, nearly half of China's sandy coasts are experiencing varying degrees of erosion and degradation.

Figure 33. Severe Erosion and Degradation of Sandy Coasts

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

(4) Spatial Distribution Overall Characteristics: "More in the South, Less in the North, Sparse in the Middle"

The overall distribution of sandy coasts in China is markedly unbalanced, with a significant scarcity of sandy beaches in the central coastal regions. As the coastal zone is a key area for economic development, the demand for sandy coastal tourism resources in China is evident. This mismatch between regional demand and supply presents a natural limitation to the economic development of China's sandy coasts.

From a spatial perspective, while sandy coasts are widely distributed across China, they are generally scattered, with varying scales of sandy coasts present in different coastal provinces. In North China, sandy coasts are primarily developed along both sides of Liaodong Bay and the Shandong Peninsula. In contrast, the southern regions are more developed, especially in the central and southern parts of Fujian, as well as in Guangdong, Guangxi, and Hainan provinces, which are major areas for sandy coast distribution.

From a geomorphological perspective, the sandy coasts in China are influenced by complex tectonic backgrounds, diverse climates, and hydrodynamic environments, leading to their development in various geomorphic units.

3. Genetic Types of Sandy Coasts

China's large latitudinal range, diverse tectonic backgrounds, varied sediment sources, and different hydrodynamic environments result in complex and diverse sandy coastal geomorphological development. There is no universally accepted classification principle or standard for coastal geomorphology types. Xia Dongxing et al. [22] classified the coastal section from Houtouya to Lanshantou on the Shandong Peninsula into five sections and four types using the wave – tide action index K as an important parameter: straight coasts, lagoon – barrier coasts, low-flat coasts, and headland – bay coasts. Zhuang Zhenye et al. [23] studied the distribution of sand bars on the Shandong Peninsula and classified sandy coast geomorphology into three types: headland – bay coasts, barrier – lagoon coasts, and straight coasts, with barrier – lagoon coasts further divided into barrier type, sand spit type, and tombolo type. Cai Feng et al. [24] classified beaches in South China into three types based on genesis and geomorphic combinations: headland – bay type, barrier – lagoon type, and straight type, summarizing the basic types and characteristics of beaches in South China. This handbook optimizes China's sandy coast classification system based on previous research and understanding of the characteristics of sandy coasts nationwide.

(1) Headland–Bay Type

Headland – bay coasts are characterized by alternating distributions of bedrock headlands and drowned valley bays, with headlands undergoing erosion and bays experiencing deposition and expansion, exhibiting both erosional and depositional coastal processes. The headland – bay type is the most widespread type of sandy coast in China, with the following genesis characteristics and main depositional geomorphic features:

① Directly backed by bedrock coasts or small-scale Quaternary sedimentary layer coasts.

② The bay often forms an independent geomorphic unit, with beach sediments mainly sourced from surrounding terrestrial and coastal erosion materials or sediments brought by small mountain streams flowing into the bay.

③ Characterized by lateral sediment transport along the coast, sediments are primarily redistributed by the lateral components of asymmetric wave-induced currents in the nearshore area.

④ In smaller or narrower bays, small "pocket" beaches often form.

⑤ In wider bays, spiral-shaped beaches with tangential and sheltered segments can form, extending more than 1 km in length.

Figure 34. Headland-Bay Type of Beach [18] (Source: Cai et al., 2019)

(2) Barrier–Lagoon Type

Barrier – lagoon-type beaches refer to beaches located on the seaward side of barrier – lagoon system barrier bars (offshore sandbars). The general geomorphological characteristics of this type of sandy coast are as follows: they usually form within headland bays or bay mouth areas, with one end of the barrier bar connected to the land and the other extending seawards; the offshore bar and the beach form a single genetic unit; and the beach adjusts itself to changes in dynamic conditions and sediment supply to maintain a dynamic equilibrium in terms of sediment transport, generally resulting in a concave arc or semicircular shoreline, with larger scales potentially forming spiral shapes. Factors such as incident wave characteristics, coastal planforms, and seabed topography determine the redistribution of coastal sediments and their movement patterns. Given the variable dynamic environments along the coast of China' s tectonic uplift zones, the depositional morphology and genesis of offshore sandbars are complex and diverse and can be broadly categorized into four basic genetic types: sand spit type, tombolo type, offshore bar type, and composite large sandbar type.

Figure 35. Barrier–lagoon type of coast [18] (Source: Cai et al., 2019)

(3) Wave-Dominated Delta Plain Type

Wave-dominated delta plain-type beaches in China are mainly developed in tectonically uplifted zones (especially the South China Uplift Zone) in the context of fault basins and fault zones formed during the neotectonic period. These beaches are found in coastal areas of river deltas with significant sand supplies, such as the Changle Minjiang Delta Plain in central Fujian, the Chenghai Hanjiang Delta Plain in eastern Guangdong, the Wuchuan Jianjiang Delta Plain in western Guangdong, the Haikou Nandujiang Delta Plain in northern Hainan, and the Changhua River Delta Plain in western Hainan. Additionally, beaches along the western coast of Taiwan's fold zone in the Taoyuan-Hsinchu and Taichung-Yunlin sections, formed by wave-controlled alluvial fans and marine terraces, also belong to this type. Since the relative stabilization of sea levels following the Holocene transgression, these coasts have experienced river sand supply conditions, and under strong wave action, river runoff and waves form the controlling dynamic system at the delta front, resulting in the formation of sandy beaches. Due to the rapid progradation of the plain coast and the lack of headlands to block incident waves, almost the entire coastal section is directly affected by waves. Over a long-term self-adjustment response process, a long, straight, and wide beach has formed.

4. Functions and Values of Sandy Coasts

(1) Functions of Sandy Coasts

Beaches are significant geomorphological units of sandy coasts located at the interface between the land and the sea. They are crucial marine natural resources in coastal areas and serve three main functions: hazard prevention and mitigation, ecological maintenance, and tourism and recreation.

Natural Protective Function: Beaches act as natural protective barriers for sandy coasts, playing a crucial role in dissipating wave energy, defending against marine hazards, and protecting people's lives and property. Due to their dynamic geomorphological evolution, beaches can quickly adjust to changing hydrodynamic environments, effectively resisting extreme events such as storm surges and typhoon waves. They also adapt to sea-level rise and the intensification of extreme events caused by global climate change. The coastal protection function of beaches is safe, efficient, sustainable, and offers high coastal resilience, which is unmatched by other coastal engineering facilities.

Ecological Function: Beaches provide excellent habitats for coastal flora and fauna and breeding grounds for important protected species, such as sea turtles and Chinese horseshoe crabs, and act as filters for pollutants. They play an irreplaceable role in maintaining the health of coastal ecosystems. Protecting beach resources means preserving the ecological environment and maintaining the integrity of marine ecosystems.

Social Function: Beaches are valuable natural tourism resources. Their well-known "3S" (Sun, Sand, Sea) attributes make them important tourist and recreational destinations. Currently, beaches are major destinations for coastal tourism, significantly contributing to the development of the coastal tourism industry. According to the United Nations World Tourism Organization (WTO), coastal tourism has become an essential part of the blue economy, accounting for 5% of the world's GDP and providing 6% to 7% of jobs. Although China's coastal tourism industry started late, it has developed rapidly, with increasing public demand for beach tourism. The coastal tourism economy has become a new growth point for the social and economic development of coastal areas.

(2) Values of Sandy Coasts

Due to their unique functions and associated values, sandy coasts have always been among the most precious and important natural resources for human society. The value of beaches can be divided into use value and nonuse value (Figure 38). The former includes socioeconomic value and natural economic value, while the latter includes existence value, bequest value, and option value. The rational development and utilization of beach resources can enhance urban quality, improve living environments, and bring enormous economic benefits. Beaches generate an average economic value of 400 billion yuan per year[13], supporting the coastal tourism industry, which accounts for nearly 50% of the marine output value (Figure 39). Coastal tourism is one of the strategic industries driving the high-quality development of China's marine economy.

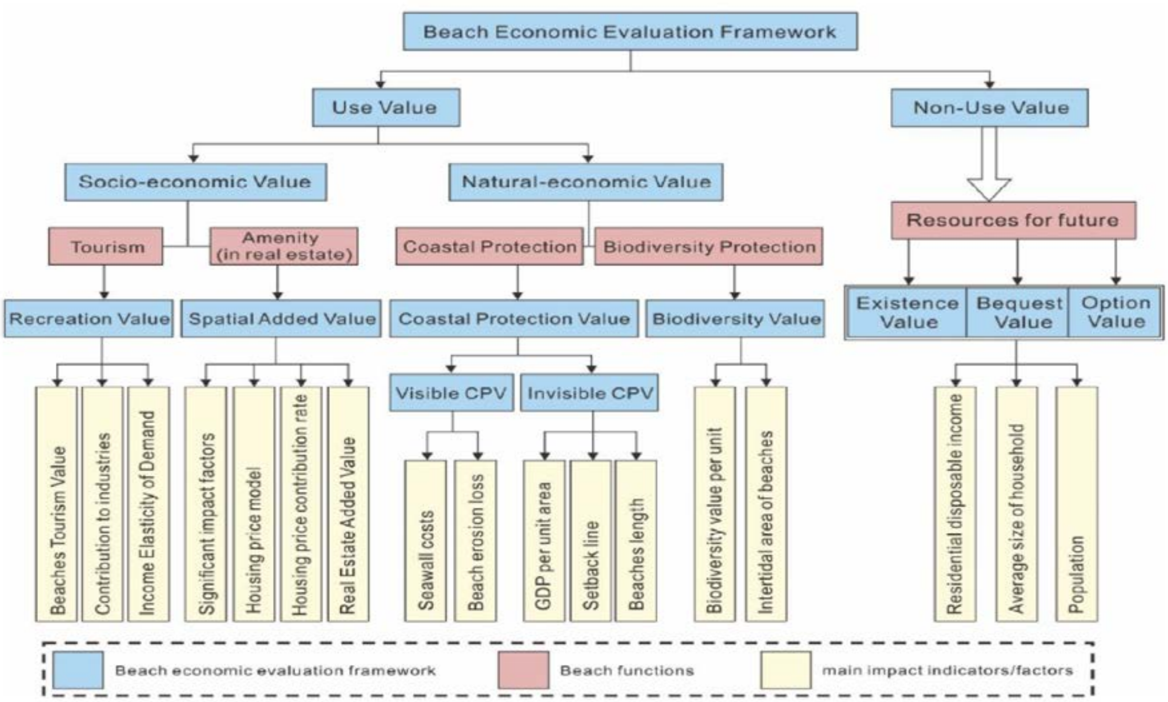


Figure 38. Use and Non-use Values of Beaches[13] (Source: Liu et al., 2023)

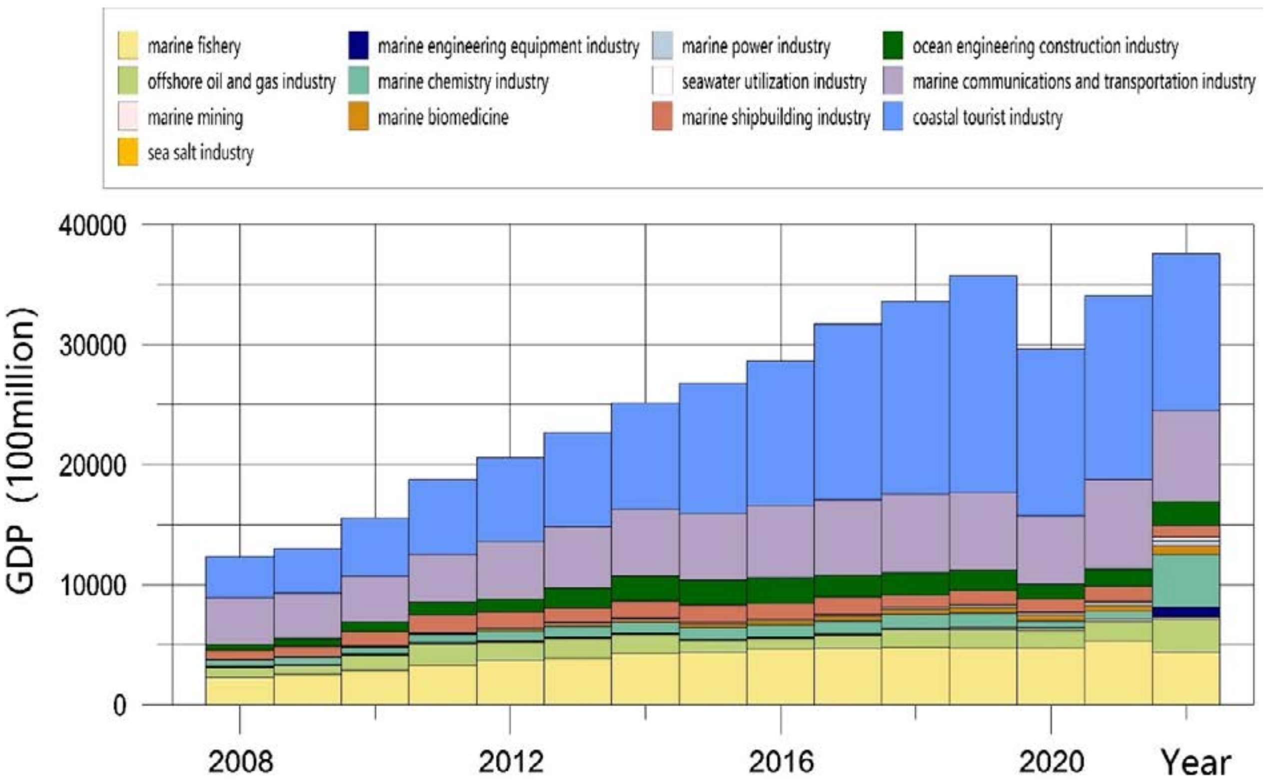


Figure 39. Contribution of Coastal Tourism to the Marine Economy

(Source: Third Institute of Oceanography, Ministry of Natural Resources)

5. Fundamental Theories of Coastal Morphodynamics

(1) Transformation of the Beach Profile Morphology

Based on research over the past few decades on coastal dynamic processes, two representative beach profiles are generally recognized: the bar type and the berm type, the latter also known as the step type, as shown in Figure 40. A step-type beach is a beach profile without an alongshore sandbar. Johnson[25] named this type of beach a normal beach or summer beach. The bar-type beach is a beach profile with an alongshore sandbar, named a storm beach or winter beach by Johnson. The winter beach is characterized by a gentler foreshore slope and nearshore sandbars, while the summer beach is depositional, featuring a steeper foreshore slope and nearshore steps replacing sandbars. These two profiles can transform into each other, mutually constraining and jointly controlling beach processes.

Coastal erosion often occurs after a significant storm. A single large storm can cause the coastline to retreat several meters to tens of meters. The eroded sediment is transported offshore, decreasing the beach slope in the nearshore area and resulting in the accumulation of a submerged sandbar. The formation of submerged sandbars causes waves to break further offshore, weakening the waves that reach the nearshore area and thus protecting the coast. The beach profile gradually adapts to the stormy season, forming a bar profile characterized by sandbars. After the storm season, there is a relatively calm period with reduced wave energy, dominated by swell waves. During this period, sediment gradually moves back towards the shore, forming a berm that continually grows, causing the shoreline to advance. When the sandbars formed during the storm season completely disappear, the sediment is entirely pushed towards the shore, forming a steeper berm profile (step profile), also known as a swell profile. Throughout the year, the beach profile transitions between these two types in response to changes in hydrological factors.

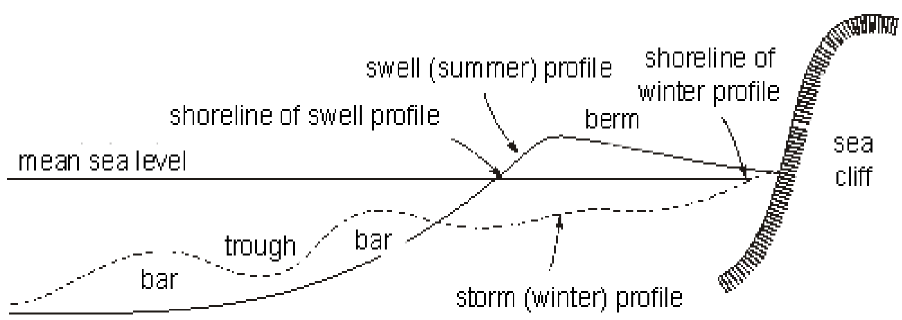


Figure 40. Illustrations of Bar-Type and Berm-Type Beach Profiles[26] (Source: Komar, 1976)

Masselink and Short[6] applied the parameters relative tide range (RTR) and dimensionless fall velocity (Ω) to analyse the interactions and mutual adaptations of beach sediments in response to waves, tides, and currents, classifying beaches into eight main types (Figure 41). Based on their classification criteria, the primary dynamic environments suitable for the development of sandy beaches can be determined.

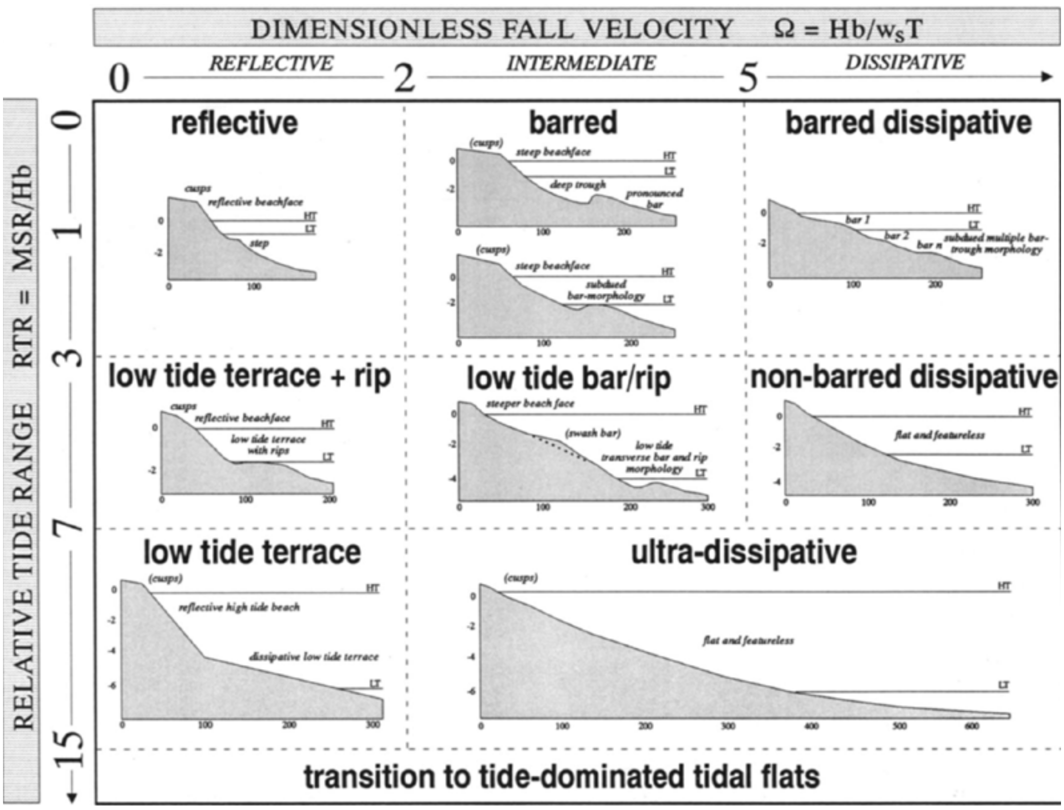


Figure 41. Masselink and Short's Beach Profile Classification[6]

(Source: Masselink & Short, 1993)

(2) Depth of Closure

The deepest limit of seasonal effective wave action on a sandy beach profile, known as the depth of closure, is an important concept in coastal engineering (Figure 42). The shape of the beach profile is usually confined within a certain range. Hallermeier[27] introduced the concept of the depth of closure for active sandy coasts in his research on beach profile changes. Above this depth, sediment movement is active, while below this depth, changes are minimal or negligible.

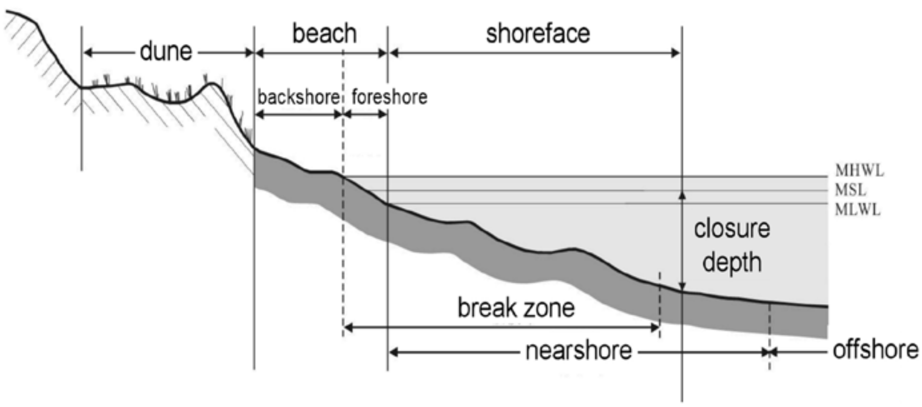


Figure 42. Schematic of the Sandy Coast Profile and Depth of Closure [4]

(Source: Cai et al, 2015)

The approximate equation for the depth of closure is given by[27-28]:

$$h_* = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$

where:

H_e is the effective wave height that is exceeded for 12 hours or 0.14% of the time annually.

T_e is the corresponding wave period for H_e.

H_e can be determined using the annual mean effective wave height $\overline{H}$ and the wave height standard deviation σH:

$$H_e = \overline{H} + 5.6\sigma_H$$

Notably, the Hallermeier formula does not consider sediment grain size, which introduces some discrepancies with the definition of the depth of closure.

Birkemeier[29] evaluated the Hallermeier equation through more accurate field observations and recommended different constants for the Hallermeier equation:

$$h_* = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right)$$

Additionally, the following simplified approximate relation was found to match the measured results well:

$$h_* = 1.57H_e$$

As mentioned earlier, the depth of closure is essentially an engineering concept used in the design of sandy coast restoration projects. Notably, the defined relationship between h_* and H_e suggests that the depth of closure may vary between years. Furthermore, in sandy coast restoration projects, the initial profile is relatively steep, and due to gravity, sediments may migrate beyond the depth of closure.

(3) Coastal Sediment Management

The objective of coastal sediment management is to integrate planning, engineering, and activities within coastal zones, estuaries, and river systems. This approach aims to expand the scope of problem solving from localized engineering scales to larger regions defined by natural sediment processes (Figure 43). Regional sediment management can identify changes in natural systems and their associated ecosystems, as well as the responses of individual projects within limited spatial and temporal frameworks.

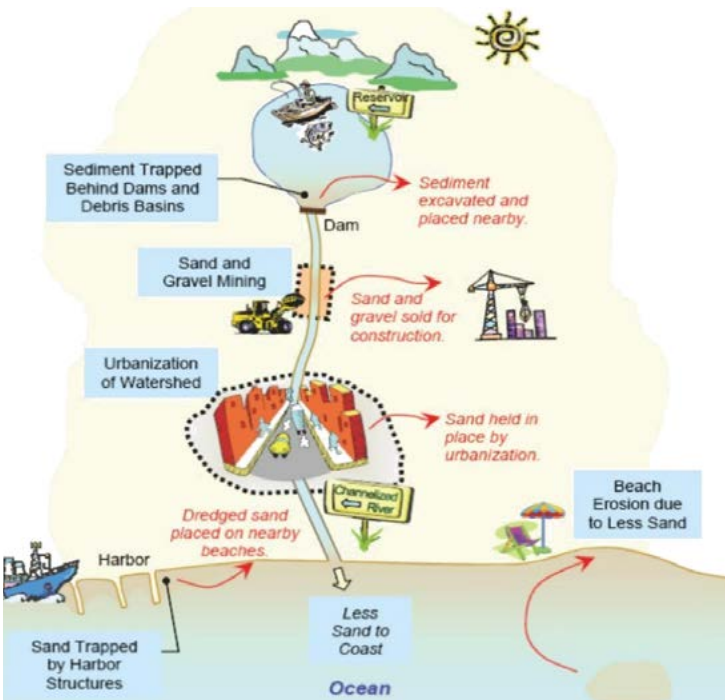


Figure 43. Schematic Diagram of Coastal Sediment Sources, Sinks, and Transport Systems[30]

(Source: Liu et al, 2022)

Regional sediment management is an important aspect of sediment budgeting within a region. It helps determine the alongshore sediment transport rates, transport patterns and paths, and locations of erosion and deposition and identify the causes and scales of changes in beach and water depth within the region. By assessing sediment budgets, the impacts of activities that alter the total amount of sediment can be predicted.

Coastal sediment management faces several challenges, primarily in reasonably determining the boundaries of coastal units (also known as sediment cells or sediment units), fully understanding sediment transport paths, and addressing uncertainties in sediment budget calculations. There are two important steps in coastal sediment management: coastal unit delineation and sediment budget calculation.

① Coastal Unit Delineation

Coastal units refer to areas within which coastal processes and their geological impacts are generally consistent. The boundaries of these units are typically significant geomorphic features, such as headlands or river mouths, that effectively separate the processes within one unit from those in adjacent units. These boundaries act as natural barriers to sediment transport, making the area between them a semiclosed system with quantifiable sediment sources and sinks. The coastal unit approach involves understanding the sediment mobility and transport mechanisms within or between sediment units, and it has been adopted by many countries for coastal management at various spatial scales.

② Sediment Budget Calculation

The use of sediment budgets to determine coastal erosion and accretion is a long-standing practice in coastal geomorphology. According to the principle of mass conservation, whether the sediment volume within a coastal unit increases, remains stable, or decreases determines whether the coastline will experience long-term accretion, stability, or erosion. The sediment budget calculation involves considering all potential sediment sources, transport paths, destinations, and modes of transport. The core task is to evaluate the contributions and losses of sediment based on the calculation procedure to determine the net gain or loss of sediment within a specific coastal unit. This approach aids in understanding sediment sources, sinks, and transport paths and has been widely used in coastal science, engineering, and management.

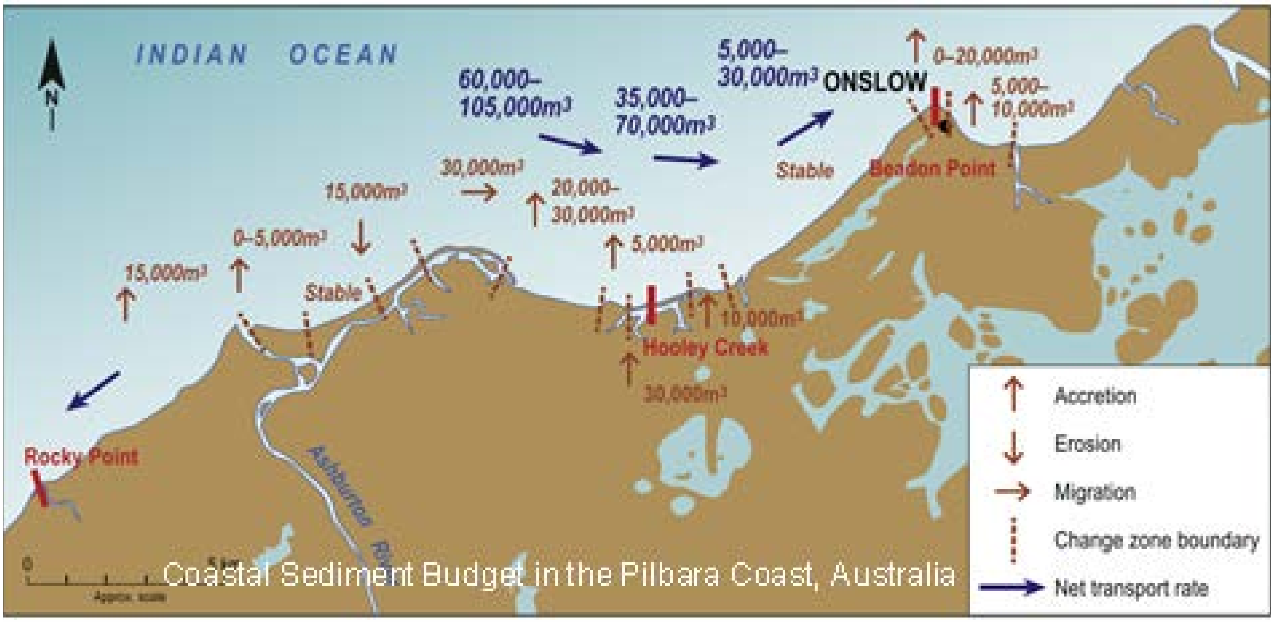


Figure 44. Conceptual Diagram of Sediment Budget in the Pilbara Coast, Australia[31-32]

(Source: Eliot, 2013)

6. Development Trends in Ecological Restoration of Sandy Coasts

Sandy coasts are valuable spatial resources, and the demand for coastal beaches is increasing both domestically and internationally. With the promotion of the concept of coastal protection based on natural processes internationally and the advancement of Xi Jinping's ecological civilization in China, sustainable ecological restoration technologies for sandy coasts, primarily through beach restoration, are bound to be widely applied. More diverse technical methods and more advanced restoration concepts will also continue to develop.

(1) Expansion of Sandy Coast Restoration Technologies

From the perspective of global sandy coast restoration practices, most projects involve the restoration of eroded and damaged sandy coasts, typically in environments conducive to beach development. However, sandy coast restoration projects in China are highly diverse and include same-phase beach nourishment, rocky beach nourishment, muddy beach nourishment, and biogenic debris coast nourishment. Nonetheless, beach restoration technologies for complex coasts still need further development. Expanding the application of beach restoration to coasts with unsuitable dynamic environments involves several approaches. Using pebble beach nourishment technology can restore beaches in severely eroded areas, enhancing coastal protection capabilities. Implementing technologies to enhance local dynamics and remove silt can facilitate beach restoration on weak dynamic coasts, increasing coastal recreational spaces. Optimizing land reclamation and seawall projects through beach restoration technologies involves constructing beaches in suitable areas in front of seawalls to enhance sandy coast protection capabilities and resist storm surges and other extreme dynamic events. Beach restoration technologies should be considered essential for coastal zone protection and restoration.

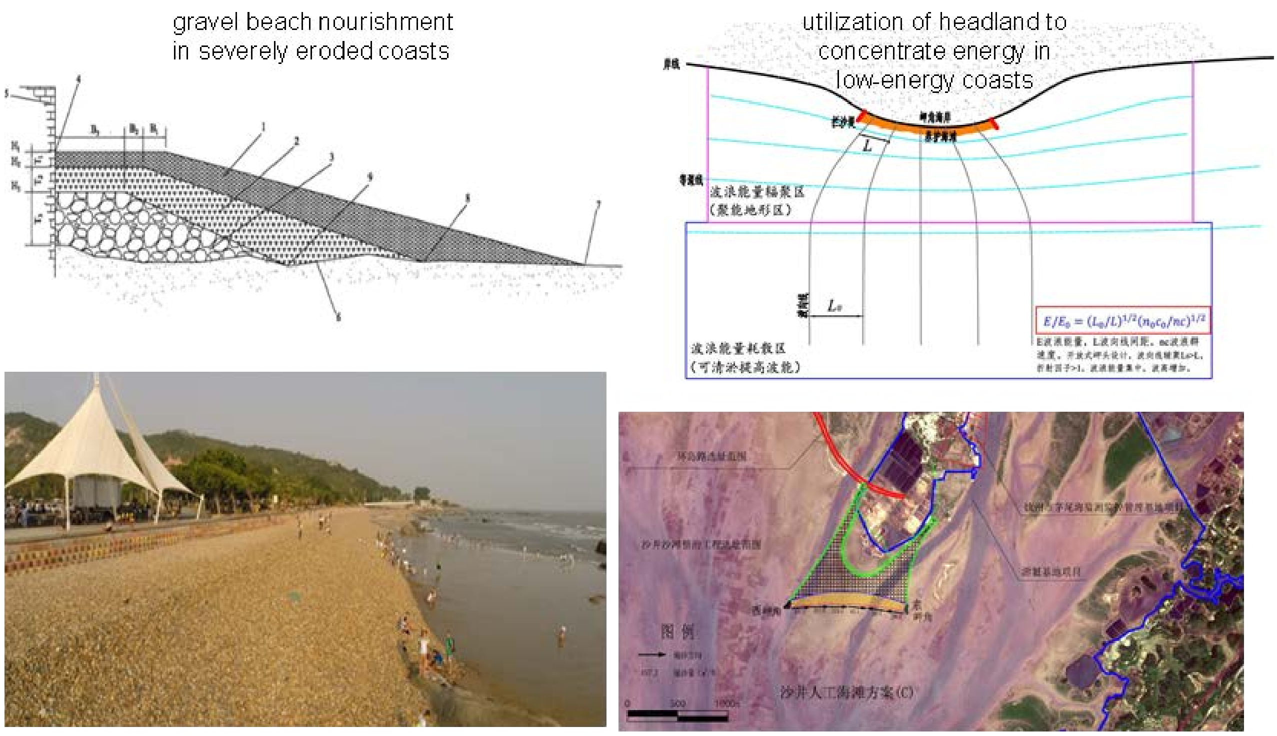
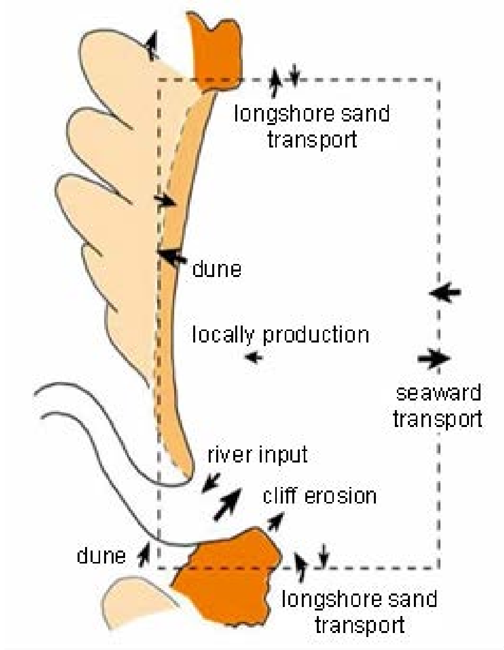


Figure 45. Expansion of Sandy Coast Restoration Technology in Complex Dynamic Environments
(Source: Third Institute of Oceanography, Ministry of Natural Resources)

(2) Sandy Coast Restoration Based on Sediment Management

Regional sediment management involves managing regional sediments from a systemic perspective, coordinating coastal engineering projects related to sediments within the region, and expanding the approach to address coastal zone issues in broader natural sediment units. By establishing sediment flow dynamics between and within sediment units, analysing sediment budgets inside and outside the system, and creating a comprehensive sediment management framework, this approach has been widely used in coastal science, engineering, and management. Sandy beach restoration, as a human-mediated redistribution of coastal zone sediments, should be integrated into the broader framework of coastal zone sediment management. Restoration considerations should extend from the damaged coast segment to the entire sediment unit system in order to analyse the sediment redistribution process in beach restoration from the perspective of regional sediment transport, the sediment budget and the overall restoration benefits generated. Sandy coast restoration based on sediment management is a method for achieving systematic coastal zone restoration, fundamentally addressing the issues of sandy coast damage and reducing potential negative impacts.



(3) From Geomorphological Systems to Ecosystem Considerations

A beach is not only a geomorphological system but also an ecological system, serving as an important habitat, spawning ground, and feeding area for marine organisms. Beach organisms are typically adapted to the high-energy environment of the beach but may struggle to withstand the rapid changes in habitat conditions brought about by beach restoration. Sandy coast restoration can negatively impact beach ecosystems through direct burial of benthic organisms, damage to organisms due to high turbidity during construction, and changes in sediment composition affecting benthic animals. However, practice has shown that these negative impacts are usually temporary and can be mitigated by improving construction methods to reduce the impact on coastal ecosystems. In the long term, sandy coast restoration has significant benefits for the environment and for organisms, providing habitats for various species and forming coastal ecosystems with high biodiversity.

Overall, current sandy coast restoration projects primarily focus on the stability of the beach geomorphological system, with insufficient attention given to ecosystem restoration technologies. Comprehensive consideration from geomorphological systems to ecosystems is the future trend in sandy coast restoration technology. This process involves the following:

Enhancing Ecosystem Impact Assessments for Sandy Coast Restoration: This step involves establishing restoration evaluation methods that encompass both geomorphological and ecological aspects.

Optimizing Beach Restoration Design and Construction Techniques Based on Ecosystem Considerations: This step includes aspects such as sediment design, selection of restoration timing, layout of restoration units, and construction intervals.

Combining Foreshore Geomorphological Restoration with Backshore Vegetation Restoration: Comprehensive backshore vegetation communities should be built to provide habitats for organisms such as birds.

(4) Protection and Restoration of Sandy Coasts Under Global Sand Deficit Conditions

Due to the extensive demand for infrastructure construction, land reclamation, and coastal restoration projects, global sand resources are rapidly decreasing, heralding an era of sand deficit. Concurrently, global sea level rise imposes greater demands on sandy coast restoration, significantly escalating restoration costs. In recent years, with the regulation of marine sand mining in China, the cost of restoring sandy coasts has increased nearly fivefold. Therefore, addressing sand resource shortages is a core issue for the future protection and restoration of sandy coasts. The following recommendations for sandy coast restoration are proposed:

Evaluate the Necessity and Sufficiency of Sandy Coast Restoration Projects: For general coasts, natural erosion retreat lines can be set to achieve coastal balance through natural erosion.

Strengthen Coastal Zone Sediment Management: Strictly prohibiting artificial sand mining should be implemented to reduce sediment loss within sediment units.

Conserve Sand Usage: In suitable coastal restoration and maintenance areas, artificial sand can be used as a substitute for natural sand.

Construct Static Headland－Bay Beaches: For coasts capable of developing static headland－bay beaches, the goal should be to create balanced shorelines. For coasts with significant sediment transport, periodic maintenance and restoration can be conducted using cyclic nourishment methods.

After nearly a century of development and application, beach restoration and nourishment have become the primary techniques for sandy coast protection and remain the best options for coastal defence worldwide. With the advancement of shoreline restoration techniques that combine geomorphic and ecological systems, nature-based coastal protection methods and concepts such as "Engineering with Nature" and "Living Shorelines" are increasingly emphasized. As the principal technology for sandy coast restoration, continuous improvements in beach nourishment and restoration will result in broader applications[33].

In China, sandy coast restoration began late but has developed rapidly, with diverse types of shoreline restoration. In recent years, under the requirements of ecological civilization construction, China has implemented several key coastal zone restoration projects, such as the "Blue Bay" and "Coastal Zone Protection and Restoration Project," and more than one hundred coastal maintenance and restoration projects have been completed, enhancing coastal defence capabilities and expanding coastal space. Sandy coast restoration, primarily through beach nourishment and restoration, has become the core technology for hazard prevention and mitigation, natural resource management, and ecological restoration in coastal zones and will undoubtedly spur further vigorous development in ecological civilization construction.

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