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T/CAOE 21.4-2020

Technical guideline on coastal ecological rehabilitation for hazard mitigation —
Part 4: Coral reefs

海岸带生态减灾修复技术导则 第4部分：珊瑚礁

（English Translation）

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Contents

Foreword

The T/CAOE 21 *Technical guideline on coastal ecological rehabilitation for hazard mitigation* consists of the following eleven parts:

——*Part 1: General;*

——*Part 2: Mangroves;*

——*Part 3: Salt marshes;*

——*Part 4: Coral reefs;*

——*Part 5: Seagrass bed;*

——*Part 6: Oyster reef;*

——*Part 7: Sandy coast;*

——*Part 8: Technical guide for the ecological construction of sea walls (trial);*

——*Part 9: Renovation of island-connecting sea wall and coastal engineering;*

——*Part 10: Directives for sea dike ecological construction of sea reclamation and enclosure project;*

——*Part 11: Supervising and monitoring.*

This is part 4 of the T/CAOE 21.

This part is drafted in accordance with the rules given in the GB/T 1.1-2009.

This part was proposed by the *Marine Early Warning and Monitoring Division, Ministry of Natural Resources*.

This standard was prepared by *China Association of Oceanic Engineering*.

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Technical guideline on coastal ecological rehabilitation for hazard mitigation —
Part 4: Coral reefs

1 Scope

This part of T/CAOE 21 specifies the working procedure, data collection and field survey, suitability assessment, implementation plan preparation, coral reef ecological restoration, follow-up monitoring and restoration effect assessment, quality control, and achievements and archiving.

This part is applicable to coral reef restoration activities for the coastal ecological rehabilitation for hazard mitigation, and other coral reef restoration works for reference as well.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this standard. At time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below.

GB/T 12763.2 Specification for Marine Surveys — Part 2: Marine hydrologic observations

GB/T 12763.3 Specification for Marine Surveys — Part 3: Marine meteorological observations

GB/T 12763.4 Specification for Marine Survey — Part 4: Survey of chemical elements of sea water

Specification for Marine Observations - Part 2: Coastal observations

Technical Guidelines for the Investigation and Assessment of the Status of Coastal Ecosystems - Part 5: Coral reefs

Technical guideline on coastal ecological rehabilitation for hazard mitigation - Part 1: General

3 Terms and definitions

The following terms and definitions apply to this document.

3.1

coral reefs

underwater ecosystems held together by the skeleton-like calcium carbonate structures secreted and formed over time by corals.

3.2

scleractinian corals

a general term for coral species with zooxanthellae, calcium carbonate skeleton and reef-building capacity under scleractinia and hexacorallia.

3.3

coverage rate

the ratio of the vertical projection length (or area) of a certain organism (or substrate) to the length of the transect line (or the area of the quadrat).

3.4

hard coral recruitment

the number of coral larvae per unit area.

3.5

coral sexual reproduction

the reproductive gametes produced by the parents of coral are combined by sperm and egg cells to form a fertilized egg, from which the fertilized egg develops into a new individual's reproductive mode.

3.6

coral asexual reproduction

a reproduction mode of corals in which a new larvae forms by extratentacular or intratentacular budding.

3.7

artificial reefs

a three-dimensional structure artificially made of limestone, concrete or ceramic to provide a substrate for the settlement of coral larvae.

4 Working procedure

The working procedure shall be performed in accordance with the requirements specified in section 6 of T/CAOE 21.1-2020.

5 Data collection and field survey

5.1 Data collection

Information for reef ecological rehabilitation for hazard mitigation includes project area conditions, corals, reef habitats, reef-dwelling organisms, threat factors (human activities and natural disasters). See Table 1 for the specific elements, acquisition methods and application scope.

Table 1 Contents of the survey on ecological rehabilitation for hazard mitigation of coral reefs

Category	Survey items	Survey elements	Acquisition methods	Range of application		
				Assessment of disaster mitigation function	Suitability assessment	Ecological effect assessment
Project area conditions	Natural conditions	Regional location, scope, landform, coastal protection status	Data collection	★	★	
	The local policy	The alignment with laws, regulations and plans	Data collection		★	

Coral	Coral communities	Hard coral species, live coral coverage rate, coral mortality rate, hard coral recruitment, coral bleaching and disease, coral damage, survival rate (transplantation)	Data collection + field survey	★	★	★
Coral reef habitats	Sea water	Salinity, pH, DO, nitrate, nitrite, ammonia nitrogen, total nitrogen, total phosphorate, active phosphate, chlorophylla, suspended solids, oils	Field survey		★	
	Hydrology and meteorology	Water temperature, transparency, depth, waves, currents, tidal levels, annual rainfall	Data collection + field survey	★	★	
	Sediment	Sediment grain size, sedimentation rate and sediment cover in reef area	Field survey		★	
	Substrate	The coverage rate of reef, gravel, sand, mud, etc.	Field survey	★	★	
Reef-dwelling organisms	Coral fishes	Species, abundance and body length range	Field survey		★	★
	Macrobenthos	Species and density of macrobenthos commonly found on coral reefs	Field survey		★	★
	Macroalgae	Type and coverage rate	Field survey		★	★
Human activities	Coastal engineering	Information of on-going and recently completed coastal engineering projects, such as those for reclamation, embankment, wharf, bridge and trestle, etc., scope and area of coral reef encroachment	Data collection + social investigation + field survey		★	
	Dredging, quarrying, sand mining	Scope and volume of dredging, quarrying and sand mining in coral reef areas in recent five years	Data collection + social investigation + field survey		★	
	Tourism development	Tourism development related to coral reefs in recent five years	Data collection + social investigation + field survey		★	
	Sewage and thermal discharge	Discharge information of sewage and thermal discharge in coral reef distribution area and nearby sea area	Data collection + social investigation + field survey		★	
	Fishing	Fishing in coral reef distribution areas in recent five years	Data collection + social investigation + field survey		★	
	Aquaculture	Aquaculture in coral reef distribution areas in the past five years	Data collection + social investigation +		★	

			field survey			
	Surface and seabed artificial facilities	Conditions of artificial installations on the surface and seabed of coral reef distribution areas	Field survey		★	
	Marine litter	Types and quantity of marine garbage on the surface and under the sea in the distribution area of coral reefs	Field survey		★	
	Accidents	accidents such as shipwrecks, stranding, chemical spills, oil spills, etc. in the distribution area of coral reefs and surrounding waters in the past five years.	Data collection + social investigation		★	
Natural disasters	Typhoon and storm surge	Information on typhoon affecting the target area in the past five years	Data collection		★	★
	Extreme heat or extreme cold	Data on extreme high or low temperatures affecting the target area in the last five years	Data collection		★	★

5.2 Ecosystem status survey

5.2.1 Ecosystem status survey

5.2.1.1 Survey elements

The survey elements are shown in Table 1.

5.2.1.2 Survey methods

According to different survey elements, the survey methods are divided into three categories: biological ecology, environmental ecology, and threat factors. The specific methods are as follows:

a) Biological ecology

Table 2 Biological ecological survey methods

Contents		Requirements
Coral communities	Hard corals species	Following T/CAOE 20.5-2020 7.3.
	Live coral coverage rate	
	Coral mortality rate	
	Hard coral recruitment	
	Coral bleaching and disease	
	Coral damage	The percentage of the damaged coral cover along the transect is derived by dividing the number of 10cm scale points by 500 following the Line Intercept Transect (LIT) method. Types of coral reef damage are determined based on: (1) Displacement: coral reefs deviate from their original position; (2) Overturning: Coral reefs deviate from their original position and are in a state of overturning; (3) Breakage: the coral skeleton breaks into two or more parts;

		(4) Abrasions: Slight breakage or abrasions of some of the coral's bones.
Coral fishes		Following T/CAOE 20.5-2020 7.2, 7.5 and 7.6.
Macrobenthos		
Macroalgae		

b) Ecological environment

Table 3 Survey methods of ecological environment

Contents			Requirements
Sea water			In conformity with the provisions of GB/T 12763.4
Meteorological			In conformity with the provisions of GB/T 12763.3
Hydrology	Wave	Observation time	During a storm surge
		Observation depth	Sea area around near the restoration site
	Wave	Observation technical requirement	(1) In conformity with the provisions of GB/T 12763.2; (2) Before the storm, a wave observation instrument shall be installed at the typical transects (generally no less than 3 stations, and the transects shall be infirmity with those specified in Annex A) in the restoration site, and the sampling frequency shall be not less than 2Hz. The method of wave observation in reef area and nearshore shallow waters is as follows: An observation array consisting of three tide gauges is arranged, and the transverse range covers the forereef slope, reef flat and nearshore area. The elevation difference between adjacent instruments is 0.1m-2.0m, and the sampling frequency is generally not less than 2Hz.
	Current	Observation time, station layout and technical requirement	In conformity with the provisions of GB/T 14914.2-2019
	Water level		
Sediment			In conformity with T/CAOE 20.5-2020 7.10, 7.11 and 7.12
Substrate			
NOTE: The depth base levels involved in the survey are local average sea levels.			

c) Threat factors

The survey indicators, survey scope, survey frequency and technical requirements for the identification of threat factors (human activities and natural disasters) should be in conformity with the requirements of 7.13 and 7.14 in T/CAOE 20.5 - 2020.

5.2.1.3 Survey frequency

At least one survey of ecosystem status should be conducted before implementing the restoration project

The status of the ecosystem should be tracked and monitored year by year in the process of ecological restoration. At least two times of survey should be carried out within 2-3 years after the completion of ecological restoration project. The surveys for corals, reef habitats and threat factors should be carried out once a year, and other elements should be surveyed seasonally.

In case a typhoon or storm surge occurs during the field survey period, the survey should be resumed within 10 days after the typhoon alert is lifted.

5.2.2 Field observation of disaster mitigation function

5.2.2.1 Selection of observation transects and stations

The transects selected for the observation should be typical and representative. 2-3 transects each with at least 2 stations should be set up. In case of 2 stations, one should be most seaward and the other most landward.

5.2.2.2 Observation elements and methods

Field observation elements include wave height and tide level at seaward and landward stations. The observation method of wave elements and water level, such as wave height and period, shall be implemented in accordance with relevant provisions specified in GB/T 12763.2.

5.2.2.3 Observation time

The field observation period should include the entire storm surge impact period (from 1d - 3d before the alert to the lift of the alert of the storm surge).

6 Suitability assessment

6.1 Ecosystem background status assessment

The ecosystem background status assessment is carried out in accordance with the requirements specified in T/CAOE 20.5-2020 10.

6.2 Assessment of disaster mitigation function

6.2.1 Assessment index

The assessment index is wave dissipative rate, and the calculation method is shown in formula (1):

$$R_{wL} = \frac{H_0 - H_L}{H_0} \times 100\% \quad \cdots\cdots (1)$$

where:

R_{wL}——The ratio percentage of wave height attenuation (H_0-H_L) to original wave height\ H_0 after waves pass through a coral reef with width L during storm surge;

H_0——Significant wave height at the seaward station, unit: m;

H_L——Significant wave height at the landward station, unit: m.

6.2.2 Assessment contents

Mitigation effects of coral reefs on storm surges and waves.

6.2.3 Assessment methods

Please refer to Annex A for specific assessment methods.

6.2.4 Capacity for disaster reduction

According to the wave dissipative rate, the disaster mitigation ability is divided into four grades: excellent, good, medium and poor (Table 4).

Table 4 Coral reef disaster mitigation ability corresponding to wave dissipative rate

wave dissipative rate	Level of disaster
$R_{wL} \geqslant 40\%$	excellent
$40\% > R_{wL} \geqslant 30\%$	good
$30\% > R_{wL} \geqslant 20\%$	medium

R_{wL}<20%	poor

6.3 Suitability assessment of restoration

6.3.1 Assessment index

See Table 5 for the basic indicators to determine the suitability of coral reef ecological restoration.

Table 5 Basic assessment indexes of suitability for coral reef ecological restoration

Indicators category	Index	Suitability condition	Transformation possibility
The ecological environment	Water temperature	The suitable temperature is 18 ° C-30 ° C, the most suitable temperature is 23 ° C-27 ° C	Difficult to transform
	Salinity	The normal salinity is 27~40, and the optimum salinity is 34-37	
	pH	The average pH range suitable for reef coral growth is 8.1-8.25	
	Water depth, light penetration depth	The water depth is less than 15 meters, ensuring that the light intensity of the area is greater than 2% of the surface	
	Wave, current	The appropriate wave, current intensity and threshold value are affected by coral species and topography, which are adapted to local conditions. Try to avoid choosing areas that are often affected by natural disasters such as typhoons	
	Pollutant	In conformity with the first class of the national water quality standards	It is difficult to renovate, so measures should be taken to improve water quality. The time limit is too long
	Sediment	Water quality is clear (transparency >3m); the average suspended matter concentration is lower than 10mg/L and the deposition rate is lower than 10mg/ (cm^2•d)	
	Substrate	A harder substrate, such as bedrock or rocks	Reconfigurable, solid base
Biological ecology	Coral communities	There are no unknown or unsolvable stressors that cause death, bleaching, or disease of corals	Difficult to transform
	Macroalgae	Areas with low coverage rate of macroalgae	Retrofit, artificial release and enemy removal
	Herbivore fishes and macrobenthos	Areas with high diversity and density of herbivore fishes and macrobenthos	
	Coral enemy organisms	Areas with lower coral enemies such as *Acanthaster planci* and *Drupella*. The number of *Acanthaster planci* is less than 15 per hm^2 and the number Drupella less than 2 per m^2	
Planning and human interference	In conformity with Plans	In conformity with the local zoning and planning, far from the marine dumping site, saltern, power plant cooling water intake and drainage outlets, docks, waterways, etc.	Difficult to transform, need coordinated regional planning
	Coastal engineering construction	No large coastal structures affecting sediment and benthic communities	
	Aquaculture	No large area mariculture activity around	
	Tourism and inhabitants	A restoration site should never be near the area with dense human activities, such as tourist areas and living areas	

6.3.2 Suitability judgment of the restoration site

The candidate restoration site can be classified into suitable restoration site, transformable restoration site and inappropriate restoration site. The judgment is as follows:

— The site with all the suitability conditions in Table 5 are satisfied and feasible for implementation is classified as the suitable restoration site.

— The site with all the suitability conditions of ″difficult to be transformable ″ in Table 5 are satisfied, but feasible for implementing restoration after the transformation may be classified as the transformable restoration site.

— The site with all the suitability conditions of any "difficult to be transformable" in Table 5 are not satisfied, or not feasible for implementing restoration even after transformation, conflict with local planning and has large environmental impact may be classified as the inappropriate restoration site.

7 The preparation of the implement plan

The implementation plan shall be prepared in accordance with the requirements specified in section 7.3 of T/CAOE 21.1-2020.

8 Ecological restoration of coral reefs

8.1 Habitat restoration

8.1.1 Substrate stabilization

Before coral reef restoration, it is necessary to confirm whether the substrate conditions are degraded. If degraded, the substrate should be stabilized. Common methods include:

— Laying steel wire mesh or interlocking concrete blocks on gravels;

— Using artificial biological reefs to stabilize coral reef substrate detritus.

8.1.2 Biological stocking and enemy organism removal

Confirm whether the biological community is degraded before a coral reef restoration project. If the biological community is degraded, biological stocking and enemy organism removal should be carried out. Common methods include:

— Releasing Herbivore fishes (e.g., Siganus fishes, damselfishes, butterfly fishes, surgeonfishes, etc.) and macrobenthos (e.g., sea urchins, Trochidae snails, etc.) to control the algae population at the restoration site;

— Artificially removing coral enemies such as *Acanthaster planci* and *Drupella*.

8.2 Coral larvae cultivation

8.2.1 Selection of species for coral larvae cultivation

Candidate species for coral larvae cultivation should refer to the historical and current data of coral reefs at the restoration site. If there is no relevant historical data at the restoration site, the data of the surrounding coral reefs of the same type can be used for reference. The selection principles of species are as follows:

— The candidate species should be dominant species or historically distributed species at the restoration site or adjacent sea areas;

— The candidate species have high tolerance to environmental limiting factors at the restoration site;

— Both the growth rate and transplant survival rate of cultivated larva should be taken into account and a mix of various species is recommended for the transplantation.

8.2.2 Sexual reproduction and breeding

The specific procedures of sexual reproduction and breeding of corals are as follows:

a) Collection of coral spermiovum cells of corals. From March to June every year, coral spermiovum cells are collected several nights before the full moon (usually 2h to 4h after sunset) when the water temperature reaches 26℃ for the first time. The net is made of bolting cloth for zooplankton nets. At the top of the net, a collection bottle is installed to collect the cells.

b) Indoor induced metamorphosis and settlement. The collected cells are fertilized and developed in an indoor incubator. A substrate of terracotta with coralline algae is added to induce coral larvae to attach.

c) Larva cultivation. After months or a year of indoor cultivation or nursery cultivation, the coral larvae grow to the size available for transplantation (at least 1 cm).

8.2.3 Asexual reproduction and breeding

The specific procedures of coral asexual reproduction and breeding are as follows:

a) Selection of breeding sites. The suitability assessment of the breeding site should be consistent with the suitability assessment of coral restoration and conformed with the requirements proposed in 6.3.

b) Nursery installation. The vertical piles of the nursery frame are driven into the bottom of the sea with a hammer, and then the other nursery frames are assembled together. After assembly, a marking float ball is deployed near the nursery.

c) Collection of coral chips. Collection of coral chips should follow the following principles:

—— Coral seedlings have legitimate sources;

—— The selected donor corals should be healthy adults, large individuals and free from bleaching, disease or death of partial tissues;

—— The size of a chip is generally 0.5cm-5cm, and the collected coral tissue should not exceed 5% of the donor coral;

—— The collection time should not be the coral breeding season;

—— Coral chips should be collected from a large area.

d) Transport of coral seedlings.

Water temperature should not be over 30℃ during transportation, and strong light and shaking avoided.

e) Fixation of coral seedlings.

The methods to fix the seedlings onto the nursery include the fixing by glue, binding, cuttage grafting and hanging. Suitable fixing methods can be selected according to the shape of the coral chips.

f) Underwater seedling tending. Underwater tending is conducted quarterly, including pest and disease control, algae removal, dead coral replacement, and nursery framework maintenance.

8.2.4 Bottom seeding transplantation

After the coral larvae are cultured to the transplantable specification, the coral graft blocks are removed from the nursery and transported to the restoration site for bottom seeding transplantation. The specific process of coral seeding transplantation is as follows:

a) Choice of transplantation site. The site suitability assessment should be consistent with the coral restoration suitability assessment and conformed with the requirements proposed in 6.3.

b) Selection of size of chips for transplantation. The survival rate of transplanted coral is closely related to the size of chips transplanted, and the survival rate of larger transplanted chips is relatively higher. The standard size varies with different species and locations, and the range of transplanted coral chips is generally between 5cm and 10cm.

c) Transplantation way. The transplanted chips are fixed by direct seeding, cottage grafting, glue fixation and binding fixation. Reasonable selection is made according to the type of transplanted corals to ensure that the transplanted corals can be tightly fixed on the substrate.

d) Density and width of transplanted corals. The density of transplanted corals is recommended to be no less than 15%, taking into account the coral coverage rate of healthy coral reefs in adjacent waters. In order to ensure the effect of wave prevention and disaster mitigation after transplantation, the width of transplantation is recommended to be not less than 200 meters.

e) Selection of transplantation time. Select a time period close to the optimal temperature to avoid long-term exposure of transplanted corals to the air and shorten the transportation time during transportation.

8.3 Deployment of artificial reefs

8.3.1 Design principles of artificial reefs

The common shapes of artificial reefs include ball, plate, box, table, cylinder, etc. The design of artificial reefs should follow the principles:

-- The reef should have good stability and is not easy to slip and roll;

-- The reef should be made of materials with low cost, corrosion resistance, impact resistance and not easy to damage, and without potential for sea water pollution;

-- The reef should be designed to increase surface area and form spaces of varying sizes.

8.3.2 The distribution and deployment of artificial reefs

The distribution and deployment of artificial reefs should follow the following principles:

-- The deployment of reefs and the setting of unit reefs should form into matrixes. The reefs with different shapes, types and materials should be selected as far as possible, and the reefs should be arranged in orderly intervals.

-- The direction of the reef should be set crossing with the direction of the current;

-- Selection of reasonable reef spacing and arrangement to increase the attraction of reef organisms;

-- The slope in front of artificial reefs should form a certain slope (slope top angle ⩾120o) to achieve the desired effect of reducing storm surge, wave and other marine power disasters; the reef flat should also reach a certain length (not less than 200 meters) to increase the friction loss along the reef.

8.4 Maintenance

8.4.1 Maintenance frequency

In the initial stage of transplantation, the maintenance frequency should be once a week. After the survival rate of corals tends to be stable, the maintenance frequency can be reduced to once a month to once a quarter.

8.4.2 Protective measures

Common protective measures include:

-- Survival of transplanted corals is regularly observed, and replacement transplantation should be carried out when the survival rate is less than 75 %;

-- Monitor the growth status of transplanted corals and timely clean out the diseased or bleached individuals or tissues;

-- Remove diseases, pests, fouling organisms and alien invasive organisms timely, and prevent and control coral enemies;

— Control the size of algae by means of artificial removal or enhancement of herbivorous fishes;

— Regularly clean up marine garbage at the restoration sites.

9 Follow-up monitoring and effect assessment

9.1 Follow-up monitoring and investigation

9.1.1 Tracking and monitoring

Execute in accordance with the requirements proposed in 5.2.

9.1.2 Post-disaster investigation

Execute in accordance with the requirements proposed in 5.2.

9.2 Effect Assessment

9.2.1 Assessment of disaster mitigation function

Perform in accordance with the requirements specified in 6.2.

9.2.2 Ecological effect assessment

9.2.2.1 Assessment index

Perform in accordance with the requirements specified in T/CAOE 20.5, 10.

9.2.2.2 Selection of reference

The effect of coral restoration is assessed by making reference to coral reefs before the restoration and adjacent without restoration activities. It shall be carried out in accordance with the requirements specified in T/CAOE 20.5-2020 10.2.

9.2.2.3 Assessment time and frequency

It is advised to assess the restoration effect of coral reef annually within 2-3 years after the restoration is completed. The assessment of disaster mitigation effect should be carried out 5 to 10 years after the restoration project is implemented.

9.2.2.4 Assessment methods

The assessment methods consist of single index assessment and multi-index synthetic assessment as follows:

A) Single index assessment

For the restoration of species diversity of coral and other biological communities, the recovery rate of each index is calculated by taking the index before the ecological restoration implementation as the reference. The calculation method is shown in formula (2):

$$P_{ij} = \frac{I_{ij} - I_i}{I_i} \times 100\% \quad \cdots\cdots (2)$$

where:

P_{ij}——Ecological restoration rate of assessment index *i* in the j year after ecological restoration;

I_i——Evaluating the background value of index i before the implementation of ecological restoration project;

I_{ij}——The value of assessment index i in the j year after ecological restoration.

According to the recovery rate, the ecological restoration trend assessed by a single index is divided into three grades: Grade I, improved significantly; P_{ij} Level II, improved; Level III, unchanged basically (Table 6).

Table 6 Assessment criteria for ecological effect of single indicator

Effect of level	Grade I/ improved significantly	Level II/ improved	Level III/ unchanged basically
	P_{ij} ≥50%	25%≤P_{ij} <50%	P_{ij} <25%

b) Multi-index synthetic assessment

According to the calculation results of a single index, the comprehensive recovery rate of coral reef ecosystem in the restored area can be obtained. The calculation method is shown in formula (3):

$$B_j = \frac{\sum_{i=1}^{n} P_{ij}}{n} \quad \cdots\cdots (3)$$

where:

B_j——Comprehensive recovery rate of coral reef ecosystem at the restoration site after ecological restoration;

P_{ij}——Ecological restoration rate of index;

n——The number of a single indicator calculated.

According to the comprehensive recovery rate B_j, the ecological restoration trend evaluated by multiple indicators is divided into three grades: Grade I, improved significantly; Level II, improved; Level III, unchanged basically (Table 7).

Table 7 Assessment criteria for ecological effect of comprehensive indicators

Effect of level	Grade I/ improvement significantly	Level II/ improved	Level III/ unchanged basically
	B_j 50% or higher	25% or less < 50%B_j	B_j< 25%

10 Quality control

Quality control shall be carried out in accordance with the requirements specified in section 8 of T/CAOE 21.1-2020.

11 Achievements and archiving

The achievements and archiving shall be carried out in accordance with the requirements specified in T/CAOE 21.1-2020 9.

Annex A
(annex informative)
Assessment methods for coral reef disaster mitigation function

A.1 Selection of assessment methods

In this paper, three methods are proposed to quantitatively evaluate the disaster mitigation function of coastal coral reefs, including field observation, physical model and numerical model. Each method follows the principle of consistency, and the error is within a reasonable range (< 10%).

In principle, the selection of assessment methods should be combined with the site conditions, economic conditions, technical equipment and experimental conditions. When conditions permit, the first priority should be given to field surveys to directly measure and calculate the wave height attenuation rate of coral reefs during a storm surge. When conditions are limited, such as there is no storm surge impact assessment area in recent years, and field surveys during a storm surge event cannot be carried out, other methods shall be used. If the physical model experimental conditions permit, the physical model can be used for the assessment, to ensure that the prototype parameters and marine hydrodynamic parameters are true and reliable; when using numerical simulation for assessment, attention should be paid to the selection of reliable numerical model. If conditions permit, the consistency principle of each method should be followed, and the error should be within a reasonable range when empirical formula method, physical model, theoretical model and numerical model are used at the same time. In general, the results of physical model and numerical model method are prior to those of empirical formula method, and the average values of physical model and numerical simulation test results can be taken.

A.2 Field surveys

a) Applicability of field survey

Field survey is suitable for the area to be evaluated where disaster frequently occurs, and economic conditions permit. At least one typhoon storm surge should have a significant impact on the assessment area in the assessment year, causing significant storm setup.

b) Technical scheme design

In field surveys, technical schemes should be designed according to the needs of assessment of marine disaster mitigation function of coral reefs. The main contents include:

-- Selection of measuring transects and stations;
-- Elements for the survey;
-- Measuring time;
-- Measuring instruments;
-- Installation and arrangement of instruments;
-- Analysis of survey data and assessment of disaster mitigation function.

c) Measuring transects and stations

Transect survey can be adopted for the field survey. The selected coral reefs should be typical, i.e., the cross-section should be parallel to the wave propagation direction, and the distribution characteristics of coral reefs in the cross-section should represent the situation of the whole coral reef. 2-3 stations along each transect shall be set up. One station shall be set up at the seaward (the front measuring station) and the other at the landside (the back-measuring station). Several stations may be set up between the two stations if conditions allow.

d) Elements for the survey

The main purpose of field survey is to directly observe the attenuation of wave height on the coral reef, i.e., to measure the width L_v of the typical cross section of the coral reef, the wave height H_0 of the cross section to the seaward station, and the wave height H_L after the wave propagates through the coral reef cross section.

e) survey time

The survey period of ocean hydrodynamic parameters should include the whole storm surge period. Coral reef parameters should be measured before the storm surge.

f) Analysis and calculation of survey data

If the survey instrument is equipped with supporting data analysis software, the significant wave heights of each period can be obtained by directly importing the field data into the data analysis software. For the survey instruments without supporting data analysis software, the field data are the data of water surface fluctuation over time. The tide and wave can be separated first, then the significant wave height in the measurement period can be calculated by using the energy spectrum analysis method for the separated wave signals.

One observation duration can last several hours to several days, one of the most unfavorable (maximum water depth, maximum) period should be selected. The significant wave height H_0 (before the observation section) and H_L (after the observation section) are brought into formula (1) to calculate the wave attenuation rate R_{wL}.

A.3 Physical modeling

A.3.1 Applicability of physical model

In low frequency of regional marine disasters (no storm surges affecting the area to be assessed within the assessment year) or observation conditions, which make it impossible to conduct field observation, physical experiment can be used. Compared with the empirical formula method, the physical experiment has the advantage in evaluating the disaster mitigation effect of coral reefs with complex shape and uneven distribution.

A.3.2 Technical methods

A.3.2.1 Model selection

The size of the reef model used in the physical experiment can be determined according to the length similarity criterion and the structural characteristics of the coral area. The length similarity scale λ_L can be calculated as follows (A.1):

$$\lambda_L = \frac{L_p}{L_m} \qquad \cdots\cdots \text{(A.1)}$$

Where:

L_p——Feature length of the prototype;

L_m——Feature length of the model.

When the water depth in front of the reef is relatively deep (>10m), the longitudinal length and water depth of the physical model can be simulated according to the actual height of the trough instead of the similar scale of length λ_L. However, wave height in deep water should be converted to the wave height in finite depth according to the conservation of energy.

A.3.2.2 Model layout

The friction effect of coral roughness should be considered according to the distribution of coral reef. The reef height L_{vm} can be calculated as follows (A.2):

$$L_{vm} = \frac{L_{vp}}{\lambda_L} \qquad \cdots\cdots \text{(A.2)}$$

where:

L_{vp}——Characteristic width of the prototype reef;

L_m——Characteristic width of the model reef.

A.3.2.3 Water level and wave conditions

According to the characteristics of the tides and waves near the reef flat to be evaluated, the wave height and water level in the hydrodynamic parameters of the model can be calculated by using the length similarity scale equations (A.3) and (A.4). When the water depth in front of the reef is relatively deep (>10m), and the longitudinal length of the model and the experimental water depth cannot be simulated according to the scale of length similarity, the deep-water wave height should be converted into the wave height of finite water depth according to the energy conservation and then the wave generation should be carried out. The model and prototype parameters should also conform to the gravity similarity criterion, i.e., the prototype Froude number is equal to the model Froude number. According to the length similarity scale and the gravity similarity criterion, the relationship between the wave period in the model and the wave period in the real sea condition is obtained. See equation (A.5):

$$H_{0m} = \frac{H_{0p}}{\lambda_L} \quad \cdots\cdots (A.3)$$

$$\eta_m = \frac{\eta_p}{\lambda_L} \quad \cdots\cdots (A.4)$$

$$T_m = \frac{T_p}{\sqrt{\lambda_L}} \quad \cdots\cdots (A.5)$$

where:

H_{0p}——Significant wave height of prototype hydrodynamic parameters;

H_{0m}——Significant wave height of model hydrodynamic parameters;

η_p——Characteristic water level of prototype hydrodynamic parameters;

η_m——Characteristic water level of model hydrodynamic parameters;

T_p——Characteristic significant wave period of prototype hydrodynamic parameters;

T_m——Characteristic significant wave period of model hydrodynamic parameters.

A.3.2.4 Layout of flume and measuring instruments

The front end of the flume should be equipped with wave maker with active absorbing function. The model is arranged in a flume with a certain distance from the wavemaker. Set the wave damping device behind the model area. Digital wave gauge is usually used in the laboratory to measure wave propagation and attenuation in the reef flat area. The gauge can be arranged around the model area, and the number of wave gauge should be no less than 3 (one at the front, middle, and rear edges of the model area respectively).

A.3.3 Analysis and calculation of test data

The hydrodynamic parameters such as water level, wave height and period, and the width and height of reef flat are brought into the formula (A.3) -formula (A.5) by using the data obtained from model test. The significant wave height $H_0 = H_{0p}$ (before the prototype coral reef disaster reduction area to be evaluated), $H_L = H_{Lvp}$ (after the prototype coral reef disaster reduction area to be evaluated) and the assessment section reef flat width $L = L_{vp}$ are brought into formula (1) to calculate the wave dissipative rate R_{wL}.

A.4 Numerical modeling

A.4.1 Applicability of numerical simulation

When the frequency of regional marine disasters is low (there is no storm surge affecting the area to be assessed in the assessment year) or the economic and technical conditions are not allowed to use the field observation, this method can be used to assess the function of coral reef disaster reduction if the characteristics of the distribution area such as the length and width of the coral reef area, the characteristic parameters such as the type and coverage of the coral reef, the hydrodynamic conditions and the mature numerical simulation technical conditions are mastered.

A.4.2 Numerical model

The reef crest is usually submerged in shallow water under the average tidal level. Waves on the front slope of the reef are affected by the nonlinear shoaling. Wave breaking at the reef crest induce energy dissipation. After the breaking wave propagates for a certain distance, it will regenerate the wave perpendicular to the coast on the reef flat, as shown in Fig. A.1.

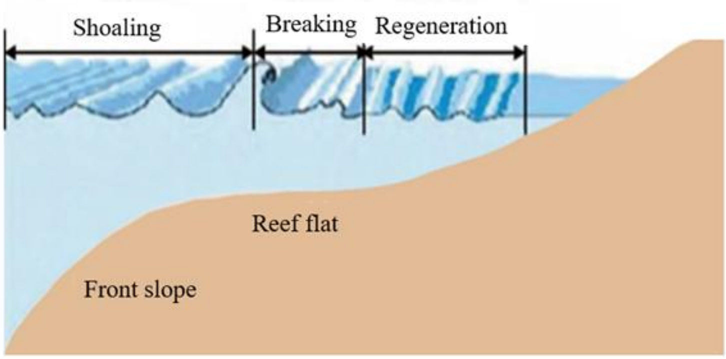

Fig. A.1 Wave propagation and deformation in coastal topography of a coral reef

Wave is affected by the rapid change of water depth and the bottom friction during the wave propagation from the deep sea to the nearshore coral reef, which causes shoaling, breaking and dissipation along the reef.

Existing modeling can simulate the current and wave propagation and modify the relevant parameters of the coral reef area to simulate the wave and current variation characteristics in this area. The other strategy is to treat reef areas as porous media.

Another type is to use a special wave-current motion model in the coral reef area, and this type of model also has different processing methods. For example, the wave-current motion fluid control equation in this area is derived by taking the reef area as a porous medium for spatial averaging. The specific numerical simulation can select the appropriate numerical model according to the actual demand and calculation ability.

This guide gives the governing equation of the wave fluid movement in the reef region, which considers the reef region as a porous medium, and the details are as follows:

In this model, the reef is regarded as a porous medium, and the N-S equation is deduced by spatial average. The governing equations of the model are shown in equations (A.6) to (A.7). The model can well simulate the propagation and attenuation process of waves in the reef region.

$$\frac{\partial\langle u_i\rangle}{\partial x_i}=0 \qquad \text{(A.6)}$$

$$\frac{\partial\langle u_i\rangle}{\partial t}+\langle u_j\rangle\frac{\partial\langle u_i\rangle}{\partial x_j}=-\frac{1}{\rho}\frac{\partial\langle P\rangle}{\partial x_i}+g_i+\nu\frac{\partial^2\langle u_i\rangle}{\partial x_i\partial x_j}-\frac{\partial^2\langle u_i{}'u_j{}'\rangle}{\partial x_j}-\langle f_i\rangle \qquad \text{(A.7)}$$

where:

$\langle u_i\rangle$——Spatial average velocity in the i (i=1, 2 in two-dimensional problems; i = 1, 2, 3 in three-dimensional problems) direction;

$\langle P\rangle$——Spatial average pressure;

ρ——Fluid density;

g_i——Acceleration due to gravity in the i direction;

ν——Fluid kinematic viscosity;

$\langle u_i{}'u_j{}'\rangle$——Spatial mean reynolds stress, k-e flow model can be used to solve;

$\langle f_i\rangle$——Spatial average reef forces.

The action force of reef $\langle f_i\rangle$ can be generalized as the drag force term and inertial force term. The drag force and inertia force acting on water body can be calculated according to equations (A.8) and (A.9) respectively.

$$f_D = \frac{1}{2}\rho C_D D u|u| \quad \cdots\cdots (A.8)$$

$$f_I = \rho C_m \frac{\pi D^2}{4}\frac{\partial u}{\partial t} \quad \cdots\cdots (A.9)$$

where:

f_D——Drag force;

f_I——Inertial force;

C_D——Drag force coefficient (which can be determined according to the characteristics of coral reefs);

C_m——Inertial force coefficient (which can be determined according to the characteristics of coral reefs);

ρ——Fluid density, unit: kg/m^3;

D——Diameter, unit: m;

u——Water flow velocity, unit: m/s.

A.4.3 Analysis and calculation of numerical simulation results

Real scale simulation should be used to evaluate the function of disaster reduction by numerical simulation. The significant wave height H_0 (before the prototype coral reef disaster reduction area to be evaluated), H_L (after the prototype coral reef disaster reduction area to be evaluated) and the assessment section reef flat width $L = L_v$ are brought into formula (1) to calculate the wave dissipative rate R_{wL}.

A.5 Selection of assessment methods

The selection of assessment methods should be considered by combining the field conditions, economic conditions, technical equipment and experimental conditions. Field observation should be first considered to measure and calculate the wave height reduction rate of coral reef flat during storm surge when conditions allowed. Other methods can be used when conditions are limited such as the absence of storm surge impact assessment areas in recent years and the inability to perform field observations during storm surge disasters. When the physical experiment conditions allowed, the physical model can be used and ensure the prototype reef flat parameters and marine hydrodynamic parameters reliable. When the numerical simulation is used for assessment, reliable numerical models should be selected to ensure the reasonable and accurate parameterization of coral reef flat.

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