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A Study of Carbon Emission Quota for Construction Period of Dredging Projects: Case Studies in Guangzhou, Shenzhen, and Malé

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Abstract

This paper develops a model to calculate carbon emissions during the construction period of dredging projects. Carbon emission quotas for various types of dredgers and auxiliary vessels in different construction conditions and geotechnical soil types during the dredging project's construction period are established, as well as the power consumption quota for management activities. Taking the construction of the main project of the cross-river channel from Shenzhen to Zhongshan (S09)'s foundation trench excavation and channel dredging, the Thilafushi Island reclamation project in Malé, and the second phase of the southern section of the Guangzhou Port Area channel maintenance project (2022–2023) as case studies, the validity of the quotas is verified. During the construction period, under the same dredging soil quality and the same working condition level, the carbon emissions of different types of dredgers are different. Conversely, under different dredging soil qualities and different working condition levels, the carbon emissions for the same dredger or auxiliary vessel are different. The carbon emissions of each dredger or auxiliary vessel increase with the increase in the ship's specifications. The carbon emissions of dredging projects are huge, with direct carbon emissions accounting for 97%, and indirect carbon emissions from equipment deployment and management activities accounting for 3%, among which the carbon emissions from electricity consumption in management activities account for only 0.3%.

Keywords: carbon emissions; quota; dredging project; construction period

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1. Introduction

In 2020, China proposed the "3060" dual-carbon target, aiming to achieve a "carbon peak" by 2030 and "carbon neutrality" by 2060. The construction engineering field has consistently been a significant source of carbon emissions. The 2022 China Building Energy Consumption and Carbon Emission Research Report disclosed that the total carbon emissions of the whole process of the construction engineering field were 5.08 billion tons, accounting for 50.9% of the national carbon emissions in 2020 (China Association of Building Energy Efficiency (2023)) [1].

In dredging projects, a large number of dredging vessels burn diesel, liquefied natural gas, or other fuels to generate construction power, producing substantial carbon dioxide emissions that have significant environmental and societal impacts.

In recent years, numerous studies have focused on carbon emissions during the construction period of engineering projects, primarily concentrating on building construction, highway engineering, municipal engineering, and urban infrastructure development. These studies have provided valuable theoretical foundations and practical guidelines for carbon emission estimation, control, and reduction. Various research efforts have examined carbon emission measurement methods, construction stage emissions, and full life cycle carbon emission calculations. Moreover, some studies have addressed the establishment of carbon emission quotas for construction projects, tunnels, and highway projects.

For example, a random forest-based predictive method was applied to estimate construction stage carbon emissions, using data from 38 buildings in the Pearl River Delta region of China as the initial training set to explore the relationship between construction stage carbon emissions and design parameters (Fang et al., 2021) [2]. The study of cradle-to-site carbon emissions through the assessment of prefabricated rebar cages (PRC) for high-rise buildings in China found that CO_2 emissions increased by 3.3 times during the transportation stage, while decreasing by 44.7% during on-site construction (Jiang et al., 2018) [3]. The empirical estimation method used to calculate CO_2 emissions in three stages of four highway projects showed that over 80% of the CO_2 emissions were generated from raw material production, while on-site construction and material transportation accounted for 10% and 3%, respectively. The total CO_2 emissions from road, bridge, and tunnel constructions were 5229 kg/m, 35,547 kg/m, and 42,302 kg/m, respectively (Wang et al., 2015) [4].

The carbon emissions from 27 prefabricated buildings showed that the embodied and operational carbon emissions of these cases varied significantly from 105 to 864 kg CO_2/m^2 and from 11 to 76 kg $CO_2/m^2/yr$, respectively, with 15.6% of embodied and 3.2% of operational carbon reductions achieved through prefabrication on average (Teng et al., 2018) [5]. Li and Chen quantitatively calculated the carbon emissions of each building's subproject during the construction period of a residential community, finding that high-rise buildings and villas had the highest unit carbon emissions of 54.51 kg/m^2, accounting for 84% of the carbon dioxide emissions produced during construction, while the unit carbon emissions for the entire residential community were approximately 54.18 kg/m^2 (Li et al., 2017) [6].

The whole life cycle method was used to establish a parametric model to evaluate carbon emissions at each stage, concluding that the usage stage was the main contributor to carbon emissions (Bonamente et al., 2015) [7]. Using a process-based method to quantitatively calculate emissions generated by material consumption, transportation, and equipment usage, the study found that carbon emissions from materials, equipment, and transportation accounted for 67%, 19%, and 14% of total building emissions, respectively (Sandanayake et al., 2016) [8]. The energy performance and environmental impact of prefabricated building modules were assessed using the life cycle assessment method. Through dynamic simulation, it was found that the material production stage accounted for 72% of emissions, while the use stage accounted for 23% (Tumminia et al., 2018) [9].

Kim and Eom pointed out that carbon reduction is one of the most pressing challenges in the shipping industry. The International Maritime Organization (IMO) has strengthened carbon emission regulations, aiming to reduce emissions to 70% of 2008 levels by 2050. However, 75% of the existing fleet fails to meet these regulations. Their study proposed a novel navigation operation method to reduce carbon emissions and extend the service life of ships without modifying the propulsion system, thus complying with carbon regulations (Kim et al., 2023) [10].

Castellano et al. designed a carbon emission estimation program for the operational phase of buildings and derived a carbon emission calculation formula to simplify assess-

ments across various cases (Castellano et al., 2015) [11]. Jun et al. proposed a BIM-based method for evaluating the total carbon emissions of buildings, improving calculation efficiency and compatibility while minimizing the impact of design changes on carbon emissions during material production, thus enabling emission predictions prior to construction (Jun et al., 2016) [12]. Cho and Chae quantified carbon emissions across the four stages of a building's lifecycle—production, construction, operation, and demolition—and conducted comparative analyses between conventional and low-carbon buildings. Their study revealed that low-carbon buildings reduce CO_2 emissions per unit area by 25% compared to conventional buildings (Cho et al., 2016) [13].

Zhang Chaohui et al. studied 39 major ports in China, using a super-efficiency SBM model to measure carbon emissions and applying a generalized difference-in-differences method to examine the impact of smart port policies on carbon emission efficiency. They found that although there is an extensive literature on carbon emissions, research specifically addressing carbon emission efficiency remains limited. The study further explored how smart port policies affect carbon emission efficiency (Zhang et al., 2016) [8].

Based on PAS2050 specifications and existing construction project consumption quotas and work shift cost quotas, some studies have developed methods to convert budget quotas into carbon emission quotas and calculate total carbon emissions (Wang et al., 2023; Zhang et al., 2024) [14,15]. Li studied the calculation of carbon emissions in the construction stage, compiled detailed carbon emission quotas in accordance with top-down decomposition principles, and summarized total carbon emission values (Li et al., 2023) [16]. Based on carbon source consumption measurements from a large-diameter shield construction project in Hengqin New District, Zhuhai, carbon emissions during construction were calculated using a carbon emission model, and a carbon emission quota for shield construction was developed (Chen, 2017) [17].

However, research focusing on carbon emission measurement methods and quotas during the construction period of dredging projects remains limited. Further theoretical and practical studies are required to better evaluate and manage carbon emissions in dredging construction activities. Furthermore, the study aligns with the global climate targets under the Paris Agreement, the International Maritime Organization (IMO) decarbonization goals, and the national climate commitments of both China and the Maldives.

Based on the concepts and theories of dredging projects and carbon emission measurement, this paper combines quota theory to construct a carbon emission measurement method and quota system for dredging projects during the construction period. The proposed method provides both a theoretical reference and practical calculation tools for carbon emission management in dredging projects, offering a scientific basis for port and marine ecological environmental protection, and promoting the sustainable development of port and waterway engineering projects.

The main contents of this paper include the following:

(1) The establishment of a carbon emission calculation model during the construction period of dredging projects;
(2) The compilation of carbon emission estimation quotas during the construction period of dredging projects; and
(3) Case analysis and validation of quota effectiveness.

2. Calculation Model

2.1. Carbon Emission Factors for Dredging Projects

2.1.1. Fuel Energy

The types of fuel consumed by different types of dredgers and auxiliary equipment during the construction period of dredging projects are mainly oil, diesel, and liquefied

natural gas, with carbon emission factors of 3174.40 kg CO_2/t, 3099.76 kg CO_2/t, and 3182.85 kg CO_2/t, respectively (China's Ministry of Housing and Urban–Rural Development (2019) [18]; Standardization Administration of China (2008)) [19].

2.1.2. Electricity

The average emission factor for the national grid, published in the Ministry of Ecology and Environment's [20] Notice on the Work Related to the Management of Greenhouse Gas Emission Reporting by Enterprises in the Power Generation Sector (2023–2025) (Ministry of Ecology and Environment (2022)) [21] and the Guidelines on the Methodology and Reporting of Greenhouse Gas Emissions by Enterprises for Power Generation Facilities (Revised Version 2022) (Ministry of Ecology and Environment (2022)) [21], is 0.5810 t CO_2/MWh.

2.2. Model for Direct Carbon Emissions

2.2.1. Model for Dredgers

Dredging vessels, such as suction hopper dredgers, cutter suction dredgers, grabs, and buckets, burn fuel energy during on-site construction, normal operation, shutdown standby, repair and maintenance, and replenishment, among other activities.

$$E_d = \sum_{i=1}^{n} \sum_{j=1}^{m} (A_i \times N_{d,i,j} \times EF_{d,j}) \quad (1)$$

where E_d represents the carbon emissions from dredger energy consumption; A_i represents the quantity of work for the i element of the project; $N_{d,i,j}$ represents the consumption of the j dredger for the i element of the project in a fixed unit (ship) shift; $EF_{d,j}$ represents the carbon emission factor for the energy consumption of the j dredger; i represents the serial number of the item content; j represents the dredger serial number.

2.2.2. Model for Auxiliary Equipment

Auxiliary equipment includes mud barges, excavators, anchor boats, tug boats, transportation vessels, and supply vessels, among others.

$$E_e = \sum_{i=1}^{n} \sum_{j=1}^{m} (A_i \times N_{e,i,j} \times EF_{e,j}) \quad (2)$$

where E_e represents the carbon emissions from energy consumption of auxiliary equipment; A_i represents the quantity of work for the i element of the project; $N_{e,i,j}$ represents the rated unit (ship) shift consumption of the j unit/ship of the auxiliary equipment put in place for the i element of work; $EF_{e,j}$ represents the carbon emission factor for the energy consumption of the auxiliary equipment; i represents the serial number of the item's content; j represents the auxiliary equipment serial number.

2.3. Model for Indirect Carbon Emissions

2.3.1. Model for Equipment

Carbon emissions from the mobilization of ships.

$$E_{dt} = \sum_{j=1}^{m} (D_{d,j} \times F_{d,j} \times E_{d,j}) \quad (3)$$

where E_{dt} represents the carbon emissions from energy consumption of ship mobilization; $D_{d,j}$ represents the transfer distance of the j ship; $F_{d,j}$ represents the energy consumption

per unit distance during the transfer of the j ship; $E_{d,j}$ represents the carbon emission factor for the energy consumption during the transfer of the j ship.

2.3.2. Model for Management Activities

This includes the carbon emissions generated by construction workers' lodging, catering and cooking, heating and cooling, lighting, use of electrical appliances, and other activities. This paper examines the indirect carbon emission accounting based on the purchased electricity consumed by the project manager's office (construction camp) and temporary facilities.

$$E_m = \sum (EL \times E_{el}) \quad (4)$$

where E_m represents carbon emissions from management activities during the construction period. EL represents the total electricity consumption of the project manager's office (construction camp) and temporary facilities. E_{el} represents the carbon emission factor for electricity.

3. Carbon Emission Measurement Quota

3.1. The Content of the Quota

The quota's content includes quota descriptions, the carbon emission quotas for suction hopper dredgers, cutter suction dredgers, grab dredgers, bucket dredgers, and mud blowers, as well as quotas for the mobilization, preparation and finishing of dredgers, construction ship carbon emission factors, adjustment values for construction ship carbon emission factors, and quotas for management activities, among others.

3.1.1. Description of the Quota

The quota consists of two parts: a general description and descriptions of each chapter. The general description, as the first part, is positioned at the top of the quota and mainly includes the basis of compilation, scope of application, measurement boundaries, and related aspects. The chapter descriptions precede the list of items for each type of ship quota, providing explanations of measurement and applicable conditions, calculation bases, working condition coefficients, and unit consumption bases for each chapter.

3.1.2. Content of the Carbon Emission Quota

The quota includes the quota number, vessel type, specifications, dredging rock and soil grades, working conditions, quantities, carbon emission benchmarks, benchmarks for over-excavation depth, extra distances, extra ship tons, bow blowing, bow spraying, mobilization modes, mobilization distances, and preparation and finishing. The contents of the items are shown in Table 1.

3.1.3. Appendix to the Quota

The appendix of the quota includes the carbon emission factors and their adjusted values for construction vessels, as shown in Table 2.

Table 1. Contents of quota items.

SN.	Quota Project Table Name	Quota Number	Ship Type and Specification	Dredged Soil and Rock Classification	Working Condition	Quota Project Quantity	Carbon Emission Benchmark	Over-Excavation Depth Benchmark	Excess Haul Distance Benchmark	Additional Turning Head Benchmark	Bow Blowing Benchmark	Bow Jet Benchmark	Deployment Method	Deployment Mileage	Startup Deployment and Completion Integration
1	Carbon Emission Quota for Trailing Suction Hopper Dredger (TSHD) Construction	√	√	√	√	√	√	√	√	√	√	√			
2	Carbon Emission Quota for Cutter Suction Dredger (CSD) Construction	√	√	√	√	√	√	√	√						
3	Carbon Emission Quota for Clamshell Dredger Construction	√	√	√	√	√	√	√	√						
4	Carbon Emission Quota for Bucket Dredger Construction	√	√	√	√	√	√	√	√						
5	Carbon Emission Quota for Blow Dredger Construction	√	√	√	√	√	√	√	√						
6	Carbon Emission Quota for Dredger Deployment	√	√		√		√						√	√	
7	Carbon Emission Quota for Dredger Startup Deployment and Completion Integration	√	√		√	√	√								√
8	Carbon Emission Quota for Shipbuilding														
9	Carbon Emission Quota for Management Activities														

Table 2. Content of appendix.

SN.	Appendix Table Name	Ship Type and Specification	Machine Shift	Working Condition	Carbon Emission Factor per Machine Shift	Carbon Emission Factor for Idle Machine Shift	Working Condition Elevation Adjustment	Carbon Emission Factor Adjustment Value
1	Carbon Emission Factor for Construction Vessels	√	√	√	√	√		
2	Adjustment Value for Carbon Emission Factor of Construction Vessels	√	√	√			√	√

3.2. Compilation of Direct Carbon Emission Quota

3.2.1. Quota for Dredgers

The 5000 m^3 suction hopper dredger is used as an example to illustrate the process of compiling direct carbon emission quotas for dredgers.

Step 1: according to *the Budget Quota for Dredging Projects* (budget quota for dredging project (2021)) [22], the work shift consumption quota per ten thousand cubic meters of working quantity for the 5000 m^3 suction hopper dredger is shown in Table 3.

Table 3. Quota for machine shift consumption of 5000 m^3 trailing suction hopper dredger. (Unit: 10,000 m^3).

Quota Number	Geotechnical Classification	Basic Quota	Over-Excavation Depth Quota	Excess Haul Distance Quota	Additional Turning Head Quota	Additional Bow Blowing Quota	Additional Bow Jet Quota
10001	1	0.715	0.014	0.111	0.103	0.863	—
10002	2	0.894	0.018	0.111	0.103	1.205	—
10003	3	1.026	0.021	0.111	0.103	—	—
10004	4	1.199	0.024	0.116	0.107	—	—
10005	5	1.323	0.026	0.116	0.107	1.085	—
10006	6	0.859	0.017	0.1	0.092	1.162	0.623
10007	7	1.02	0.02	0.1	0.092	1.238	0.7
10008	8	1.289	0.026	0.1	0.092	1.462	0.777
10009	9	1.493	0.03	0.111	0.103	1.547	—
10010	10	1.552	0.031	0.111	0.103		—

Step 2: according to *the Cost Quota of Ship Work-Shift for Dredging Projects* (cost quota of ship work shift for dredging project (2019)) [23], the diesel fuel consumption for one work-shift for the 5000 m^3 suction hopper dredger is 6547 kg. Thus, diesel fuel consumption per ten thousand cubic meters of working quantity can be calculated, and the results are shown in Table 4.

Table 4. Fuel consumption for 5000 m^3 trailing suction hopper dredger construction.

Quota Number	Dredged Soil and Rock Classification	Quota Project Quantity (10,000 m^3)	Fuel Consumption (kg)					
			Benchmark	Over-Excavation Depth	Excess Haul Distance	Additional Turning Head	Additional Bow Blowing	Additional Bow Jet
PX100001	1	1	4681.11	91.66	726.72	674.34	5650.06	
PX100002	2	1	5853.02	117.85	726.72	674.34	7889.14	
PX100003	3	1	6717.22	137.49	726.72	674.34		
PX100004	4	1	7849.85	157.13	759.45	700.53		
PX100005	5	1	8661.68	170.22	759.45	700.53	7103.50	
PX100006	6	1	5623.87	111.30	654.70	602.32	7607.61	4078.78
PX100007	7	1	6677.94	130.94	654.70	602.32	8105.19	4582.90
PX100008	8	1	8439.08	170.22	654.70	602.32	9571.71	5087.02
PX100009	9	1	9774.67	196.41	726.72	674.34	10,128.21	
PX100010	10	1	10,160.94	202.96	726.72	674.34		

Step 3: combined with the fuel energy carbon emission factor, we can establish the carbon emission quota data. The results of the construction carbon emission quota for the 5000 m^3 suction hopper dredger are shown in Tables 5 and 6. Under level 4 working conditions, the 5000 m^3 suction hopper dredger completes each ten thousand cubic meters of working quantity, and the carbon emissions from type 1 to type 10 geotechnical soil result in a 2.17 times change in baseline value. Type 1 (organic soil, peat, and silt) has the

least carbon emissions, type 6 (loose sandy soil) comes second, and type 10 (gravelly soil) has the most.

Table 5. Carbon emission quota for trailing suction hopper dredger (TSHD) construction.

Quota Number	Dredged Soil and Rock Classification	Quota Project Quantity (10,000 m^3)	Benchmark (kg CO_2)					
			Carbon Emission	Over-Excavation Depth (kg CO_2)	Excess Haul Distance (kg CO_2)	Additional Turning Head (kg CO_2)	Additional Bow Blowing (kg CO_2)	Additional Bow Jet (kg CO_2)
PX100001	1	1	14,510.30	284.12	2252.65	2090.30	17,513.83	
PX100002	2	1	18,142.95	365.29	2252.65	2090.30	24,454.43	
PX100003	3	1	20,821.78	426.18	2252.65	2090.30		
PX100004	4	1	24,332.66	487.06	2354.12	2171.47		
PX100005	5	1	26,849.13	527.65	2354.12	2171.47	22,019.13	
PX100006	6	1	17,432.66	345.00	2029.41	1867.06	23,581.78	12,643.24
PX100007	7	1	20,700.01	405.88	2029.41	1867.06	25,124.13	14,205.89
PX100008	8	1	26,159.13	527.65	2029.41	1867.06	29,670.02	15,768.54
PX100009	9	1	30,299.13	608.82	2252.65	2090.30	31,395.02	
PX100010	10	1	31,496.49	629.12	2252.65	2090.30		

Table 6. Carbon emission factor for construction vessels.

SN	Quota Number	Ship Type and Specification	Machine Shift	Working Condition	Carbon Emission Factor per Machine Shift (kg CO_2)	Carbon Emission Factor for Idle Machine Shift (kg CO_2)
1	PX201001	5000 m^3	1	IV	20,294.13	2029.41
2	PX201002	10,000 m^3	1	IV	40,768.04	4076.80
3	PX201003	12,000 m^3	1	IV	45,736.96	4573.70
4	PX201004	13,000 m^3	1	IV	48,222.97	4822.30

Step 4: According to the above steps 1 to 3, the carbon emission quota for dredger preparation and finishing can be calculated using the shift quota, fuel consumption quota, and fuel consumption carbon emission factor. The results are shown in Table 7.

Table 7. Carbon emission quota for dredger startup deployment and completion integration.

SN	Quota Number	Ship Type and Specification	Sub-Item	Quota Project Quantity	Carbon Emission Benchmark (kg CO_2)
1	PXQT1001	5000 m^3	Preparation	1 time	60,882.39
2	PXQT1002	5000 m^3	Finishing	1 time	60,882.39
3	PXQT1003	10,000 m^3	Preparation	1 time	122,304.13
4	PXQT1004	10,000 m^3	Finishing	1 time	122,304.13
5	PXQT1005	12,000 m^3	Preparation	1 time	137,210.88
6	PXQT1006	12,000 m^3	Finishing	1 time	137,210.88
7	PXQT1007	13,000 m^3	Preparation	1 time	144,668.90
8	PXQT1008	13,000 m^3	Finishing	1 time	144,668.90

3.2.2. Quota for Auxiliary Equipment

The auxiliary equipment invested in dredging construction mainly includes mud barges for transporting dredged materials, tugboats, anchor boats, and traffic vessels for assisting the dredging vessels in construction. The activities of these vessels cannot be quantified by the volume of dredging works, and therefore, it is not possible to compile carbon emission quotas corresponding to the working conditions, rock and soil types, and quantity of work, as in the case of dredging vessels. The carbon emission quotas for auxiliary equipment, based on

corresponding shifts and vessel specifications (such as power, capacity, towing force, etc.), can only be measured by fuel consumption. The carbon emission quota of auxiliary equipment, based on corresponding vessel specifications (such as power, cabin capacity, towing capacity, etc.), can only be calculated by fuel consumption. According to the method of compiling carbon emission quotas for dredger construction, we can determine the carbon emission quotas for tugboats, self-propelled mud barges, and anchor boats in terms of work shifts and non-work shifts. Taking the tugboat as an example, the results are shown in Table 8.

Table 8. Carbon emission factor for auxiliary vessels.

SN	Quota Number	Ship Type and Specification	Machine Shift	Working Condition	Carbon Emission Factor per Machine Shift (kg CO_2)	Carbon Emission Factor for Idle Machine Shift (kg CO_2)
1	TL201001	200 kW	1	IV	973.32	97.33
2	TL201002	440 kW	1	IV	2138.83	213.88
3	TL201003	970 kW	1	IV	4714.73	471.47
4	TL201004	1440 kW	1	IV	6999.26	699.93
5	TL201005	1940 kW	1	IV	9429.47	942.95
6	TL201006	2940 kW	1	IV	14,289.89	1428.99
7	TL201007	3860 kW	1	IV	18,762.85	1876.28
8	TL201008	5380 kW	1	IV	26,149.58	2614.96

3.2.3. The Effect of Changes in Working Conditions on Quota

Based on the change in fuel consumption for each type of ship under varying working conditions, the adjusted carbon emission factor is calculated, using the suction hopper dredger as an example. The results of the quota calculation are shown in Table 9.

Table 9. Adjustment value for carbon emission factor of construction vessels.

SN	Quota Number	Ship Type and Specification	Machine Shift	Working Condition	Working Condition Elevation Adjustment	Carbon Emission Factor Adjustment Value (kg CO_2)
1	PX201001	5000 m^3	1	IV	increasing in level I–III and decreasing in level V–VII	1456.89
2	PX201002	10,000 m^3	1	IV	increasing in level I–III and decreasing in level V–VII	2678.19
3	PX201003	15,000 m^3	1	IV	increasing in level I–III and decreasing in level V–VII	3003.67
4	PX201004	20,000 m^3	1	IV	increasing in level I–III and decreasing in level V–VII	3167.95

3.3. Compilation of Indirect Carbon Emission Quota

3.3.1. Quota for the Mobilization of Construction Equipment

Referring to the methods in the above chapters, quotas for the mobilization of construction equipment can be prepared based on work shift and non-work shift quotas, fuel consumption quotas, and fuel consumption emission factors during the transfer period. Taking the suction hopper dredgers as an example, the calculation results of the quota are shown in Table 10.

Table 10. Carbon emission quota for vessel deployment.

SN	Quota Number	Ship Type and Specification	Deployment Method	Round-Trip Deployment Mileage	Carbon Emission Factor Adjustment Value (kg CO_2)
1	PXDQ1001	5000 m^3	Self-propelled	100 nautical miles	73,515.40
2	PXDQ1002	10,000 m^3	Self-propelled	100 nautical miles	99,212.16
3	PXDQ1003	12,000 m^3	Self-propelled	100 nautical miles	105,257.90
4	PXDQ1004	13,000 m^3	Self-propelled	100 nautical miles	111,303.64

3.3.2. Managing Carbon Emission Quota for Management Activities

The carbon emissions from 100 MWh of electricity consumed are 58,100 kg CO_2 (Table 11).

Table 11. Carbon emission quota for management activities.

SN	Quota Number	Electricity Consumption (MWh)	Carbon Emission Factor (tCO_2/MWh)	Carbon Emission Quota (kg CO_2)
1	GL00001	100	0.581	58,100.00

4. Case Studies and Quota Validation

In order to validate the applicability and accuracy of the proposed carbon emission quota system, three representative dredging projects with different scales, construction environments, soil types, and equipment configurations were selected as case studies. These include the following:

(1) The Shenzhen–Zhongshan Cross-River Passage main project (China), representing a large-scale offshore channel dredging project;
(2) The Thilafushi Island reclamation project in Malé (Maldives), representing a nearshore land reclamation dredging project; and
(3) The second phase of the southern section of the Guangzhou Port maintenance project (China), representing a routine inland port channel maintenance dredging operation.

These cases comprehensively reflect diverse dredging construction scenarios, which help to verify the applicability and robustness of the proposed quota system across different engineering conditions.

4.1. Projects Overview

Case 1: Shenzhen to Zhongshan Cross-River Passage main project construction (S09). The total mileage of trench excavation and channel dredging is 28 km, with a total dredging volume of about 40 million m^3. The construction period is 64 months, from July 2018 to June 2023.

Case 2: Thilafushi Island reclamation in Malé, with about 5.12 million m^3 of dredging and reclamation, and a construction period of seven months from September 2023 to March 2024.

Case 3: The second phase of the southern section of the Guangzhou Port Sea Channel maintenance project (2022–2023). The total mileage of the maintenance channel is about 87 km, with a total dredging volume of about 2.34 million m^3. The construction period is three months, from December 2023 to February 2024.

4.2. Data Sources

The equipment entry and exit records include the name, specification, time, etc. Records of refueling include the fuel type, quantity, date, place, etc. Electricity consumption statistics for the project camp and temporary dock include the quantity and time period, etc. Statistics of construction ships are shown in Table 12.

Table 12. Vessel deployment for project construction.

SN	Ships Type	Shenzhen Project		Malé Project		Guangzhou Project	
		Quantity	Self-Owned	Quantity	Self-Owned	Quantity	Self-Owned
1	Trailing Suction Hopper Dredger	7	6	1	1	3	3
2	Cutter Suction Dredger	1	1				
3	Clamshell Dredger	44	2				
4	Mud Barge	149					
5	Tugboat	1	1			1	1
6	Anchor Boat	6	1	1			
7	Transportation Vessels	2					
	Total	210	11	2	1	4	4

4.3. Calculation and Verification Analysis of Each Case

4.3.1. Shenzhen Project

(1) Calculation results of carbon emissions during construction period.

The total carbon emissions during the construction phase of the Shenzhen–Zhongshan Cross-River Passage main project (S09) amounted to 440,500 tons of CO_2. Of this, direct carbon dioxide emissions accounted for 433,300 tons (98.37%), while indirect emissions contributed 7200 tons (1.63%). Based on the emission source analysis, dredging vessels were the primary contributors, releasing 278,500 tons of CO_2 (63.21%). Auxiliary equipment accounted for 160,800 tons (36.50%), whereas management activities contributed a minor 1300 tons (0.29%) (Table 13 and Figure 1).

Table 13. Summary of carbon emissions during the construction period of the Shenzhen project.

SN	Item	Direct Carbon Emissions (10,000 t CO_2)	Indirect Carbon Emissions (10,000 t CO_2)	Total Carbon Emissions (10,000 t CO_2)	Proportion
1	Dredging Vessels	27.49	0.35	27.85	63.21%
2	Auxiliary Equipment	15.84	0.24	16.08	36.50%
3	Management Activities	/	0.13	0.13	0.29%
	Total	43.33	0.72	44.05	
	Proportion	98.37%	1.63%		

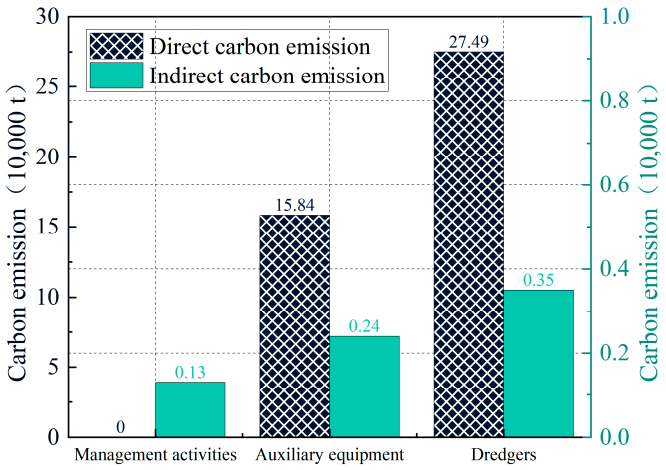

Figure 1. Column chart of carbon emission during construction period of the Shenzhen Project (unit: 10,000 tons of CO_2).

Based on the total dredging volume of 35.97 million cubic meters, the average carbon dioxide emissions per 10,000 cubic meters of dredged material amounted to 122.47 tons, comprising 120.47 tons of direct emissions and 2.00 tons of indirect emissions. Given the 60-month construction period from July 2018 to June 2023, the average monthly carbon dioxide emissions were 7342.05 tons, including 7222.29 tons from direct sources and 119.76 tons from indirect sources.

(2) Actual emission verification.

Since the project's non-owned ships operate under a non-fuel leasing model, only the carbon emissions from owned vessels—including six rake suction dredgers, one cutter suction dredger, one tugboat, and two grab dredgers—were calculated and verified based on fuel consumption data and direct carbon emissions estimated using emission quotas. The results are presented in Table 14. It was found that the direct carbon emissions calculated using the quota method were 0.75% higher than those derived from actual fuel consumption. Specifically, the emission estimates were 0.21% higher for the suction hopper dredger, 1.68% higher for the cutter suction dredger, 4.76% higher for the grab dredger, and 0.80% higher for the tugboat.

Table 14. Comparison of actual fuel carbon emissions from owned vessels and quota-based direct carbon emissions calculation.

SN	Ships Type	Fuel Combustion Carbon Emissions (t CO_2)	Quota-Based Direct Carbon Emission Calculation (t CO_2)	Difference Value	Difference Percentage
1	Suction hopper	182,598.35	182,983.22	−384.87	−0.21%
2	Cutter suction hopper	14,379.84	14,625.55	−245.71	−1.68%
3	Grab dredgers	20,188.97	21,196.99	−1008.02	−4.76%
4	Tugboats	1719.44	1733.37	−13.94	−0.80%
	Total	**218,886.59**	**220,539.13**	**−1652.53**	**−0.75%**

4.3.2. Malé Project

(1) Calculation results of carbon emissions during construction period.

The total carbon emissions during the construction period of the Thilafushi Island reclamation project in Malé amounted to 28,600 tons of CO_2. Of this, direct carbon dioxide emissions accounted for 28,200 tons (98.61%), while indirect emissions contributed 400 tons (1.39%). Based on the emission source analysis, dredging vessels were the primary contributors, releasing 27,800 tons of CO_2 (97.31%). Auxiliary equipment accounted for 752 tons (2.63%), while management activities generated 17 tons (0.06%) (Table 15 and Figure 2).

Table 15. Summary of carbon emissions during the construction phase.

SN	Item	Direct Carbon Emissions (10,000 t CO_2)	Indirect Carbon Emissions (10,000 t CO_2)	Total Carbon Emissions (10,000 t CO_2)	Proportion
1	Dredging Vessels	2.75	0.037	2.78	97.31%
2	Auxiliary Equipment	0.07	0.0014	0.0752	2.63%
3	Management Activities		0.0017	0.0017	0.06%
	Total	2.82	0.04	2.86	
	Proportion	98.61%	1.39%		

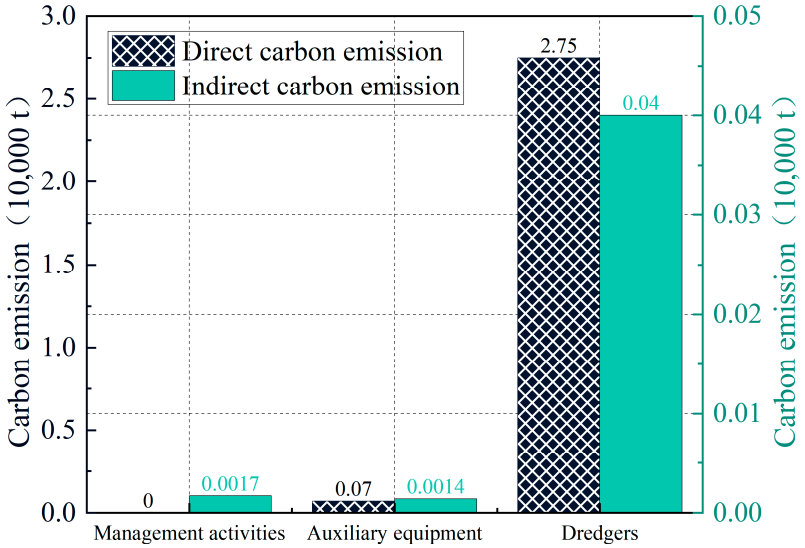

Figure 2. Column chart of carbon emission during construction period of case 2 (unit: 10,000 tons of CO_2).

Based on the total dredging volume of 5.12 million cubic meters, the average carbon dioxide emissions per 10,000 cubic meters of dredged material amounted to 58.87 tons, comprising 55.10 tons of direct emissions and 0.78 tons of indirect emissions. Over the 7-month construction period from September 2023 to March 2024, the average monthly carbon dioxide emissions were 4086.79 tons, including 4029.85 tons from direct sources and 56.94 tons from indirect sources.

(2) Actual emission verification.

It was found that the direct carbon emissions calculated using the quota method were 4.90% higher than those derived from actual fuel consumption in this project. Specifically, the suction hopper dredger exhibited a 4.88% higher emission estimate, while the anchor boat had a 5.74% higher estimate (Table 16).

Table 16. Comparison of actual fuel carbon emissions from owned vessels and quota-based direct carbon emission calculation.

SN	Ships Type	Fuel Combustion Carbon Emissions (t CO_2)	Quota-Based Direct Carbon Emission Calculation (t CO_2)	Difference Value	Difference Percentage
1	Trailing Suction Hopper Dredger	26,130.98	27,471.13	−1340.15	−4.88%
2	Anchor Boat	695.46	737.80	−42.34	−5.74%
	Total	26,826.44	28,208.93	−1382.49	−4.90%

4.3.3. Guangzhou Project

(1) Calculation results of carbon emissions during construction period.

It was calculated that the total carbon emissions during the construction period of the second phase of the maintenance project for the southern section of the Guangzhou Port Sea Channel (2022–2023) amounted to 10,200 tons of CO_2. Of these, direct carbon dioxide emissions accounted for 9600 tons (94.09%), while indirect emissions contributed 600 tons (5.91%). Based on the emission source analysis, dredging vessels were the primary contributors, releasing 9400 tons of CO_2 (92.71%). Auxiliary equipment accounted for 700 tons (7.11%), while management activities generated 19 tons (0.19%) (Table 17 and Figure 3).

Table 17. Summary of carbon emissions during the construction phase.

SN	Item	Direct Carbon Emissions (10,000 t CO_2)	Indirect Carbon Emissions (10,000 t CO_2)	Total Carbon Emissions (10,000 t CO_2)	Proportion
1	Dredging Vessels	0.89	0.05	0.94	96.97%
2	Auxiliary Equipment	0.02	0.004	0.03	2.83%
3	Management Activities		0.002	0.002	0.19%
	Total	0.91	0.06	0.97	
	Proportion	93.82%	6.18%		

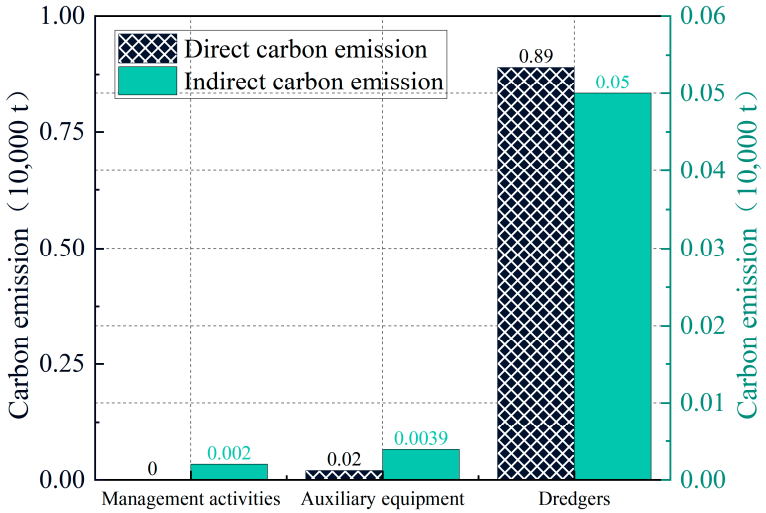

Figure 3. Column chart of carbon emission during construction period of case 3 (unit: 10,000 tons of CO_2).

The total dredging volume for this project is 2.3431 million cubic meters. Accordingly, the average carbon dioxide emissions per 10,000 cubic meters of dredged material amounted to 41.55 tons, comprising 38.98 tons of direct emissions and 2.57 tons of indirect emissions. Over the construction period from December 2023 to February 2024, the average monthly carbon dioxide emissions were 3245.39 tons, including 3044.71 tons from direct sources and 200.68 tons from indirect sources.

(2) Actual emission verification.

It was found that the direct carbon emissions calculated using the quota method were 3.65% higher than those derived from actual fuel consumption in this project. Specifically, the rake suction dredger exhibited a 3.73% higher emission estimate, while the tugboat had a 0.80% higher estimate (Table 18).

Table 18. Comparison of actual fuel carbon emissions from construction vessels and quota-based direct carbon emission calculation.

SN	Ships Type	Fuel Combustion Carbon Emissions (t CO_2)	Quota-Based Direct Carbon Emission Calculation (t CO_2)	Difference Value	Difference Percentage
1	Trailing Suction Hopper Dredger	8566.06	8897.63	−331.57	−3.73%
2	Anchor Boat	234.59	236.49	−1.90	−0.80%
	Total	8800.65	9134.12	−333.47	−3.65%

4.4. The Result Calculated by Quotas

Based on the carbon emission quotas described in the previous chapter, the carbon emissions for the three dredging projects were calculated. The results are shown in Tables 19 and 20 and Figure 4, with a total emission of 47.89 million tons, of which 47.07 million tons are directly emitted, accounting for 98.29%, and 0.82 million tons are indirectly emitted, accounting for 1.71%. In terms of carbon emissions per 10,000 cubic meters of construction volume, the Case 1 project has the highest emissions, followed by the Case 2 project, and the Case 3 project has the lowest emissions. The monthly average carbon emissions data also show the same contrast. Carbon emissions from dredgers dominated the sources (63–97%, averaging 65.84%), followed by auxiliary equipment (3–37%, averaging 33.85%), while management activities contributed the least (0.06–0.3%, averaging 0.27%).

Table 19. Summary of carbon emissions during the construction phase for three case projects.

SN	Project Title	Direct Carbon Emissions (10,000 t CO_2)	Indirect Carbon Emissions (10,000 t CO_2)	Total Carbon Emissions (10,000 t CO_2)
1	Shenzhen	433.3	07.2	440.5
2	Malé	28.2	00.4	28.6
3	Guangzhou	9.1	00.6	9.7
Total		470.7	08.2	478.9

Table 20. Carbon emissions per 10,000 m^3 and monthly average for three case projects.

SN	Project	Soil Type	Maximum Transport Distance	Carbon Emissions per 10,000 m^3 of Project Volume (t CO_2)			Monthly Average Carbon Emissions (t CO_2)		
				Direct Emissions	Indirect Emissions	Total	Direct Emissions	Indirect Emissions	Total
1	Shenzhen	1, 3, 6, 11, 12	110 km	120.47	2.00	122.47	7222.29	119.76	7342.05
2	Malé	6, 7	10 km	55.10	0.78	55.88	4029.85	56.94	4086.79
3	Guangzhou	1, 6	91 km	40.89	2.57	43.46	3044.71	200.68	3245.39
Average				72.15	1.78	73.94	4765.62	125.79	4891.41

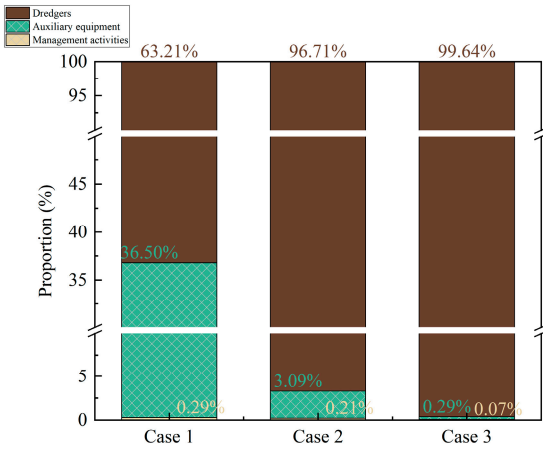

Figure 4. Percentage accumulation chart of carbon emissions during the construction period (unit: 10,000 tons of CO_2).

4.5. Validation of Actual Emissions

Since the non-owned vessels in the three cases of this paper adopt a non-fuel chartering mode, the validation of the carbon emissions for the owned vessels is verified only through fuel consumption to validate the direct carbon emissions data from the quota measurement, and the results are shown in Table 21 The difference between the direct emissions calculated by the quota and those calculated from fuel consumption in the three project cases ranged from −0.75% to −3.65%, with the direct emissions measured by the quota being slightly higher than those released by the actual fuel consumption, with an average of 1.32%. The validation data fully demonstrate that the quota data compiled in this study are reliable and practically significant.

Table 21. Comparison of actual fuel carbon emissions from construction vessels and quota-based direct carbon emission calculation in three case studies.

Sn	Project	Number of Owned Vessels	Fuel Combustion Carbon Emissions (t CO_2)	Quota-Based Direct Carbon Emission Calculation (t CO_2)	Difference	Difference Percentage
1	Shenzhen	10	218,886.59	220,539.13	−1652.53	−0.75%
2	Malé	2	26,826.44	28,208.93	−1382.49	−4.90%
3	Guangzhou Port	4	8800.65	9134.12	−333.47	−3.65%
	Total	16.00	254,513.69	257,882.17	−3368.49	−1.32%

5. Conclusions

This paper formulated the carbon emission quota during the construction period of dredging projects and verified its effectiveness using three different project cases. The principal findings of this study are summarized as follows:

(1) The results of this study show that different types of dredging vessels emit varying amounts of carbon dioxide during the construction period even when operating under the same dredging soil types and working conditions.

(2) The carbon dioxide emissions of the same dredging vessel exhibit significant variations when operating across different geotechnical soil types and working conditions.

(3) The carbon emission quotas for self-propelled dredgers during the construction period are significantly higher than those for non-self-propelled dredgers. For self-propelled dredgers, carbon emissions increase with larger cabin capacities, while for towing vessels, emissions increase with the power rating of the tugboats.

(4) Dredging construction activities generate substantial carbon emissions, which are predominantly direct emissions resulting from fuel combustion during production activities. Unlike housing and municipal engineering projects where material production and transportation dominate carbon emissions, direct emissions account for approximately 97% of total emissions during dredging construction, while indirect emissions from equipment deployment and management activities account for about 3%. The emissions from electricity consumption during management activities represent only a minor portion, approximately 0.3%.

(5) The carbon emissions during the construction period of dredging projects primarily originate from fuel consumption of construction activities. Construction enterprises should strengthen the planning, management, and control of vessel operations during the construction phase. Prior to construction, comprehensive analysis of project conditions and soil characteristics should be conducted to facilitate reasonable equipment configuration and selection. Construction schemes and equipment combinations with optimal schedules, lower costs, and minimized carbon emissions should be adopted based on multi-scheme comparisons. During construction, vessel idling and

standby periods should be strictly controlled, vessel utilization should be maximized, and overall operational efficiency should be improved to reduce unnecessary fuel consumption and associated emissions.

(6) Based on the established quota system and analysis results, several practical emission reduction strategies are further proposed to guide carbon management in dredging projects. These include (i) optimizing equipment configuration and scheduling based on project-specific geotechnical and operational conditions; (ii) adopting advanced energy-efficient dredging equipment and low-emission engines to enhance fuel utilization; (iii) minimizing over-excavation and unnecessary dredging distances through strict control of workloads; and (iv) implementing intelligent construction management systems for real-time monitoring and dynamic scheduling of vessel operations. These measures can provide valuable technical references for achieving both effective project execution and carbon reduction targets.

It should be noted that the proposed quota system focuses on construction-phase emissions based on standard operational scenarios. Variations in fuel quality, equipment efficiency, unforeseen delays, or site-specific conditions may introduce deviations from the calculated quotas. In addition, upstream emissions from equipment manufacturing and dredged material disposal are beyond the current model scope and warrant future investigation.

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Conflicts of Interest: Author Siming Liang was employed by the company CCCC Guangzhou Dredging Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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