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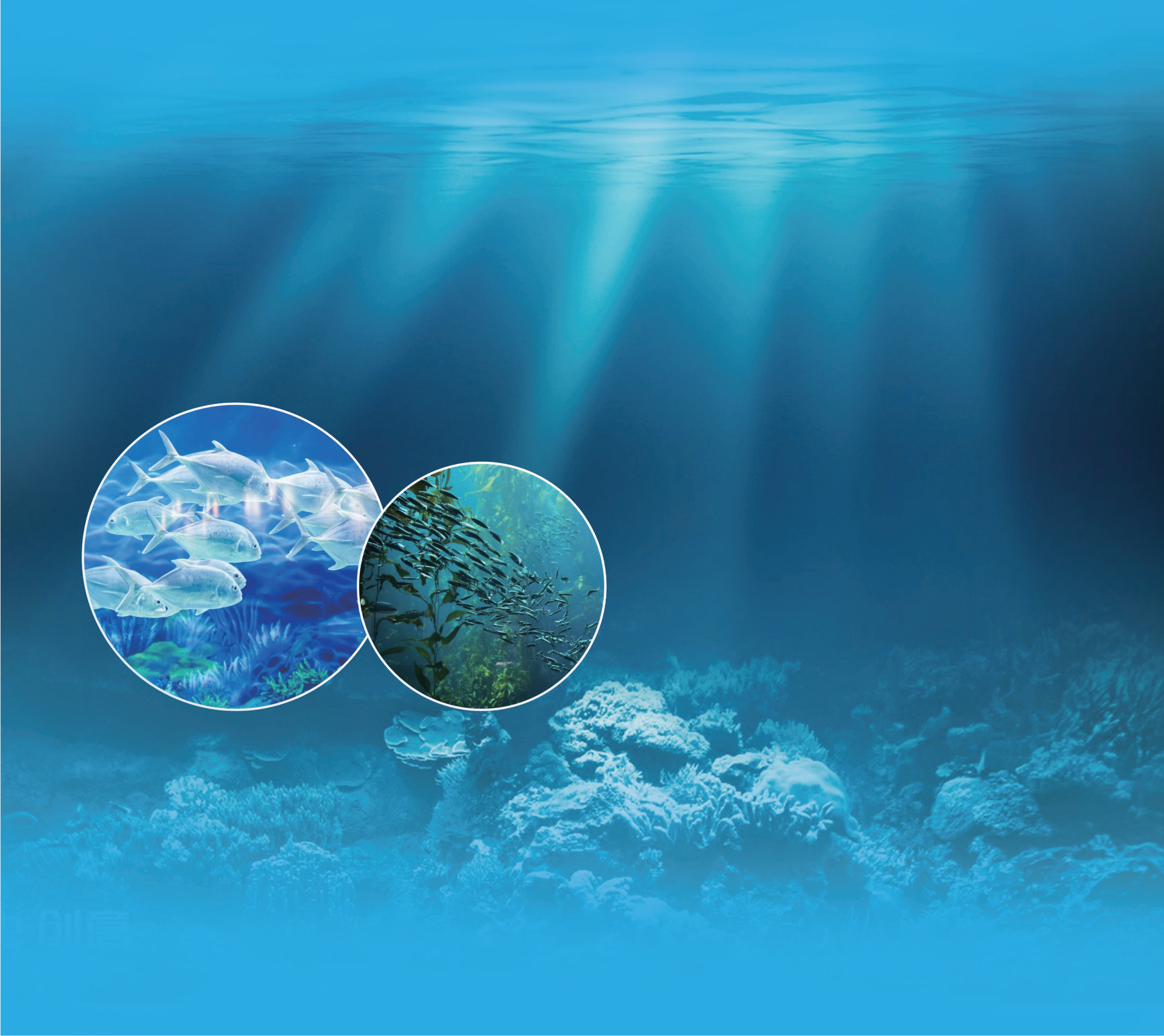

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Volume 5 | Issue 1 | March 2023 | Page 1-47
Sustainable Marine Structures

Contents

Editorial

Articles

Sustainable Marine Structures
https://ojs.nassg.org/index.php/sms

ARTICLE

Analysis of Wave Added Drag and Motion Response of Mid-high-speed Ship against Waves

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ABSTRACT

In order to accurately predict the on-wave resistance and responses to hull motions of ships in actual sea conditions, the k-ε method of the RNG model is adopted on the basis of the unsteady RANS method. The two-formula turbulence model deals with the viscous flow, the VOF method captures the free surface, the velocity boundary method makes waves, the artificial damping method is used to eliminate waves, and the nested grid technology is used to deal with the motion response of ships on waves. Combined with the 6-DOF motion formula, a three-dimensional numerical wave cell for regular waves is established. For one example, taking a KCS Container ship and fishing boat sailing at a mid-high-speed, the increase of wave resistance and motion response at different wavelengths are analyzed, and the simulation results are compared with the experimental value, the content of strip theory in potential flow theory and the panel method to prove the reliability of CFD method in predicting ship motion.

1. Introduction

In the actual navigation process, the ship will be affected by waves of different degrees and some movement phenomena, such as heave and pitch. These motions will not only increase the resistance of the ship and reduce the propulsion efficiency, but also affect the normal operation of the equipment on the ship and the working efficiency of the crew, and even cause the ship to capsize. Therefore, accurate prediction of the motion performance of the hull is very vital for ship design. Therefore, the study of ship motion characteristics in waves has become a current hot spot in academic research [1]. The traditional method of studying ship motion performance is based on potential flow theory and model tests. The theory based on potential flow has been widely used for its convenience and rapidity. Particularly in the initial design stage of a ship, in order to quickly obtain the motion performance of ships, it has been favored by ship

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designers. However, because there is a big error between the numerical simulation results and the theoretical calculation results, it is a difficult to accurate prediction of nonlinear results such as the increase of ship motion amplitude, wave breaking and waves on the deck [2]. Therefore, it is very important to obtain more flow field information at the stage of ship detailed design. Although the calculation results of the model experiment are accurate, due to a large number of manpower and costs, it cannot meet the requirements of the current fierce market competition for the rapid acquisition of new ship types. In recent years, with the rapid development of computer technology and mathematical knowledge, using CFD technology to predict wave resistance and motion performance has become a reality. CFD method not only considers the viscous effect, but also fully considers the nonlinear effect, so it has been widely used. Many research results have been published at home and abroad to predict wave resistance and motion performance using CFD. In foreign countries, for RANS formula, is solved by Orihara and Miyata [3] through the finite volume method, and used the overlapping grid technology to simulate and calculate the wave resistance and motion of container ships in regular waves. The numerical value of the DTMB5512 ship-type large-amplitude motion is calculated and summarized by Carrica and Wilson [4], which is at medium and high speed, using overlapping grid technology. Tezdogan and Kemal Demirel [5] and others evaluated the resistance and motion of container ships at low speeds following the waves using the unsteady RANS method. In China, the CFD solver name-Foam-SJTU independently developed by Shen Zhirong [6] team based on the open-source code OpenFOAM can well predict the motion performance of ships and marine engineering and has been verified by experiments. Zhao Invention [7] and others developed a CFD hydrodynamic performance calculation system for ships based on the RANS method of overlapping grids, which can well simulate the resistance and response of ship motion. Shi Bowen [8] and others set up a three-dimensional numerical simulation wave-making water channel based on the viscosity principle. In this way, the performance of ship navigation in irregular waves is simulated. However, the resistance and response of different ship types moving on the waves are different. The KCS Container ship and fishing boat are mid-high-speed ships, and there are few detailed studies on wave resistance and motion response. Based on the above conditions and experience, this paper numerically simulates the motion of fishing boats in waves in a six-degree-of-freedom regular wave numerical pool based on the unsteady RANS method, calculates the wave resistance and motion response, and verifies the reliability of this method by numerical calculation. The numerical calculation methods here include the strip theory method and panel method. The research results of this paper can provide technical support for the design and optimization of similar ships.

2. Basic Theory of CFD

The formulas followed in the calculation domain of the whole simulated pool are the continuity formula and N-S formula, and the turbulence model adopts the k method of RNG-ε. In the model, capture free liquid surface by multiphase flow model method. And the wave is generated at the given wave velocity at that border of the speed inlet, and a factitious damping setting is added wave pool exit area for wave attenuation.

2.1 Control Formula

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0 \qquad (1)$$ [9]

$$\rho\frac{\partial \overline{u_i}}{\partial t}+\rho\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j}=-\frac{\partial \overline{p}}{\partial x_i}+\mu\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j}-\rho\frac{\partial \overline{u_i' u_j'}}{\partial x_j}+\rho\overline{f_i} \qquad (2)$$

where, u_x, u_y, u_z are velocity components in x, y and z directions; t is time; ρ is the quality density of fluid; $\overline{u_i}$ is Reynolds mean velocity; $\rho\overline{u_i' u_j'}$ Reynolds stress.

2.2 Turbulence Model

The turbulence model adopts the k method of RNG-ε. In the model, the turbulent energy formula and energy consumption formula are in the following form [10]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}-\frac{\partial}{\partial x_j}[(\alpha_k \mu_{eff})\frac{\partial k}{\partial x_j}]=G_k+G_b-\rho\varepsilon-Y_M \qquad (3)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}-\frac{\partial}{\partial x_j}[(\alpha_\varepsilon \mu_{eff})\frac{\partial \varepsilon}{\partial x_j}]=c_{\varepsilon 1}\frac{\varepsilon}{k}(G_k+c_{\varepsilon 3}G_b)-c_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}-R \qquad (4)$$

where, $\mu_{eff}=\mu+\rho C_\mu\frac{k^2}{\varepsilon}$; α_k, α_ε are the reciprocal of turbulence kinetic energy's effective prandtl number and turbulent dissipation rate.

2.3 Free Face Snap

Under the condition of keeping the Euler grid unchanged, the interface between the ship and the water surface is captured by the free following of the hull surface, which is called the VOF method [11]. It can be used to simulate the multi-flow model by finding the solution of the momentum formula and volume fractions of a fluid or fluids. In any control volume, the sum of the volume fractions of all phases must be 1. For each qth phase, the formula is:

$$\frac{\partial a_q}{\partial t}+\frac{\partial(ua_q)}{\partial x}+\frac{\partial(va_q)}{\partial y}+\frac{\partial(wa_q)}{\partial z}=0 \quad (5)$$

$$\frac{\partial \alpha_q}{\partial t}+v_q * \nabla \alpha_q=\frac{S_{\alpha_q}}{\rho_q}+\frac{1}{\rho_q}\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp}) \quad (6)$$

where, a_1 and a_2 are the volume fractions of water and air respectively, and aq = 0.5, which is the limiting surface between water and air; q = 0, which represents that the entire computing domain is water; q = 1, which represents that th entire computing domain is air.

2.4 Wave Making and Wave Absorption

This wave-making adopts the velocity boundary method, which makes waves by giving the wave velocity at the boundary of the velocity entrance [12]. Compared with the physical test pool, It has high economic value, convenient operation, high calculation accuracy and slow attenuation. At the same time, this method is easier to give a fixed velocity of the vessel at the entrance boundary, which can avoid difficulties brought by moving the boundary, which is another advantage compared with the simulated physical method.

The wave surface formula is:

$$\eta = a\cos(kx-\omega_e t) \quad (7)$$

The speed influences are as follows:

$$u = a\omega_0 e^{kz}\cos(kx-\omega_e t)+U \quad (8)$$

$$w = a\omega_0 e^{kz}\sin(kx-\omega_e t) \quad (9)$$

where, a is wave amplitude. K = 2π/λ determine, which is called wave number. ω_0 is natural frequency of wave, $\omega_0=\sqrt{2\pi g/\lambda}$. ω_e can be calculated by formula: $\omega_e = \omega_0 + kU$, which is called the frequency of a wave as measured by its relative velocity and wavelength. This equation shows that ω_e varies with the change of the velocity of the vessel U.

The expression of artificial damping coefficient μ is as follows:

$$\mu\pounds(x,z)=\alpha\left(\frac{x-x_f}{x_a-x_f}\right)^2\left(\frac{z_d-z}{z_d-z_u}\right) \quad (10)$$

where, $x_f \le x \le x_a$ (f and a are the two endpoints of the resistance region in the X direction, separately); $z_d \le z \le z_u$ (d and u are the bottom along the y direction and the intersection of water and air separately); α is the damping control parameter.

2.5 DOF Equation of Motion

When establishing the ship motion formula, two reference coordinate systems are established. One is the fixed coordinate system OoXoYoZo, which is fixed on the earth. The other is the ship moving coordinate system GXYZ, which is fixed on the ship [13]. The origin of the moving coordinate system is located at the center of gravity G of the ship, where Gx, Gy and Gz are the intersection lines of the longitudinal section, the transverse section and the horizontal liquid level passing through the center of gravity G, respectively, and the downward direction of the Z axis is positive[14].

$$\frac{\mathrm{dB}}{\mathrm{dt}}+\Omega\times B=F \quad (11)$$

$$\frac{\mathrm{dK}}{\mathrm{dt}}+\Omega\times K+U\times B=M \quad (12)$$

where, Ω is the angular velocity, B is the ship's moment, F is the additional force, U is the ship's speed, K is the moment of momentum, and M is the sum moment.

3. Verification of Numerical Calculation Method

3.1 Main Dimensions of KCS Ship

KCS ship type is a medium and high-speed container ship with complete experimental data, and is a general hull for design and experiment[15]. In this paper, the additional wave resistance, heave and pitch of the KCS ship are calculated. The correctness of the CFD numerical calculation method is verified by comparing it with the experimental values. The three-dimensional model of the KCS ship is shown in Figure 1, and the main dimensions are shown in Table 1.

Figure 1. Geometric model of KCS ship form.

Table 1. Main dimensions and ship form parameters of KCS ship model and real ship.

Parameter	Unit	Ship model	Full-scale ship
Scale ratio	-	52.55	1
Length between perpendiculars (L_{PP})	m	4.3767	230
Ship width (B)	m	0.611	32.2
Draft (d)	m	0.205	10.8
Wet surface area (S)	m^2	3.436	9424
Square coefficient （C_B）	-	0.65	0.65
Froude number (Fr)	-	0.26	0.26

3.2 Computational Domain and Calculation Condition

In this paper, a three-dimensional numerical flume is established to simulate the KCS ship form. The size of the calculation area is: the distance from the entrance of the calculation area to the bow is 1.33 L, the depth of the calculation area in the Z direction is 6 L, the width in the Y direction is 2 L, and the distance from the stern to the exit of the calculation area is 4 L (where L is the length between the vertical lines of the hull, in m). The lower part of the free surface is water and the upper part is air. The boundary conditions include velocity inlet, pressure outlet and symmetrical boundary conditions. In this paper, the wavelength length ratio $\lambda/L=0.75\sim2.00$ is the calculation condition, and the motion response of KCS ship type at different wavelengths is analyzed by changing the wavelength to conduct a mathematical simulation.

3.3 Meshing

In CFD calculation, mesh division has a key impact on the calculation results and calculation speed. In this paper, the overlapping grid technology is used to divide the hull and computing domain, as shown in Figure 2 and Figure 3. The hull parts (such as the bow and stern) with sharp curvature changes are meshed to ensure that their geometric shape is basically unchanged. In addition, the free surface part that has a great impact on the calculation results has been densified to ensure that there are 80 grids in the wavelength range and 40 grids in the wave height range, and the final number of grids is about 2.4 million.

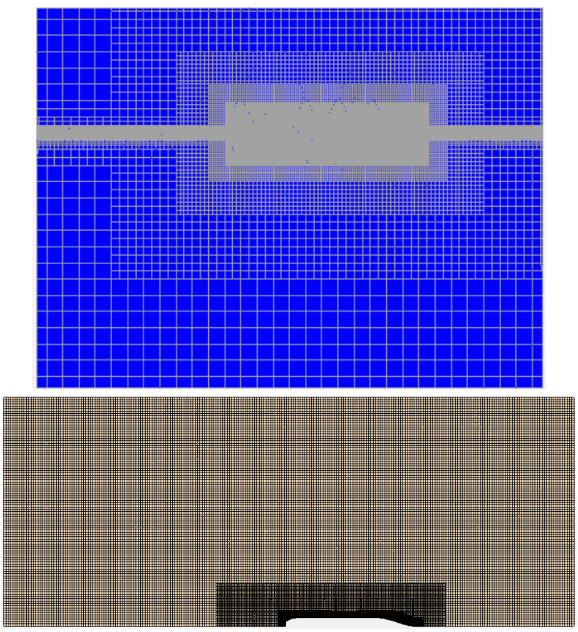


Figure 2. Calculation domain and free surface meshing.

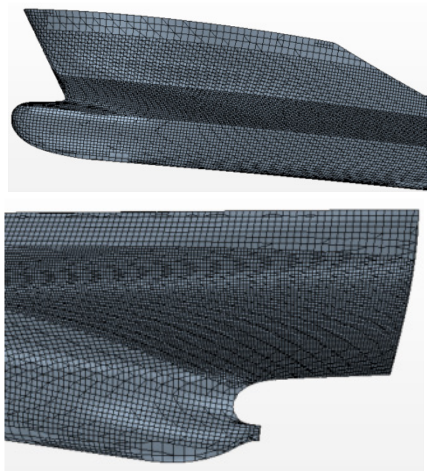


Figure 3. Hull surface meshing.

3.4 Calculation Results

3.4.1 Grid Uncertainty Analysis

The accuracy of mesh density is very important for the accuracy of results. Therefore, before numerical simulation based on the CFD method, it is necessary to use test data to analyze the uncertainty of grid division. In this paper, three sets of grid settings are set. The main difference is the basic size of the mesh. According to the grid density, the results of the three examples can be divided into S1 (coarse), S2 (medium) and S3 (fine), as shown in Figure 4.

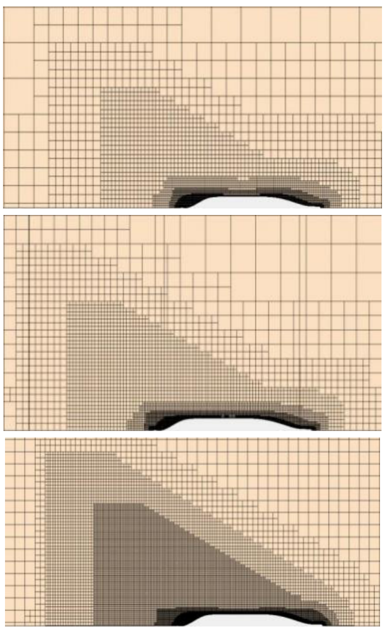


Figure 4. Grid division of three groups of density.

According to ITTC (2002), the three sets of grid refiner base size ratio ri (uniform parameter refinement ratio) are set to 1.414. The uncertainty is calculated as follows:

$$R_i = \frac{\varepsilon_{i,21}}{\varepsilon_{i,32}} \tag{13}$$

$$\delta^{*(1)}_{RE_{i,1}} = \frac{\varepsilon_{i,21}}{r_i^{p_i} - 1} \tag{14}$$

$$p_i = \frac{In(\varepsilon_{i,32} / \varepsilon_{i,21})}{In(r_i)} \tag{15}$$

$$\delta^*_{i,1} = C_i \delta^*_{RE_{i,1}} = C_i \frac{\varepsilon_{i,21}}{r_i^{p_i} - 1} \tag{16}$$

$$C_i = \frac{r_i^{p_i} - 1}{r_i^{p_{iest}} - 1} \tag{17}$$

In the formula: C_i is the Correction Factor, p_{iest} is the estimate of the first precision limit order, because the interval size is zero and reaches the asymptotic range, therefore $C_i \to 1$, $p_{iest} = 2$.

When C_i is much less than or greater than 1,

$$U_i = (|C_i| + |1 - C_i|)\left|\delta^*_{RE_{i,1}}\right|, \quad |1 - C_i| > 0.125 \tag{18}$$

$$E = D - S_1 \tag{19}$$

$$U_V \approx \sqrt{U_D^2 + U_i^2} \tag{20}$$

U_D = 2% D, D is the experimental value.

$$S_C = S_1 - \delta^*_{i,1} \tag{21}$$

$$E_C = D - S_C \tag{22}$$

$$U_{i_C} = |1 - C_i|\left|\delta^*_{RE_{i,1}}\right|, \quad |1 - C_i| > 0.25 \tag{23}$$

$$U_{V_C} \approx \sqrt{U_D^2 + U_{i_C}^2} \tag{24}$$

The total drag coefficients in the uncertainty analysis are extrapolated to full scale following ITTC 78. (Details can be referred to 7.5-02-03-01.4). The present results are valid when $|E| < U_V$ and $|E_C| < U_{VC}$. In this paper, the uncertainty of the total resistance coefficient of the KCS ship is analyzed. The results are shown in Table 2.

Table 2. Results of uncertainty analysis.

CFD CTs (10–3)			**EFD CTs (10–3)**			
S1	S2	S3	D	ri	Ri	pi
3.96	3.58	3.63	3.67	1.414	0.712	0.98
δ^*_{RE}(1)(%D)	E(%D)	U_V(%D)	E_C(%D)	U_{VC}(%D)	S_C (10-3)	U_D(%D)
4.703E-05	8.6E-05	1.2 E-04	3.897E-05	1.014E-04	3.672	0.404
	S_1		S_2		S_3	
Number of the grids	1600000		2400000		2850000	
Base size	0.08 m		0.06 m		0.04 m	

3.4.2 Comparison of CFD Calculated Value and Test Value

Figure 5, Figure 6 and Figure 7 are the comparisons of CFD simulation results and experimental values of the heave transfer function, pitch transfer function and wave additional resistance coefficient. It can be seen from the figure that the CFD calculation result is close to the experimental value, and the error is within 3%, meeting the engineering calculation accuracy requirements. Figure 8 shows the free surface wave waveform of the KCS ship type, showing the obvious shape of the Kelvin wave system. Figure 9 shows the hull surface pressure of the KCS ship type, with obvious slamming at the bow.

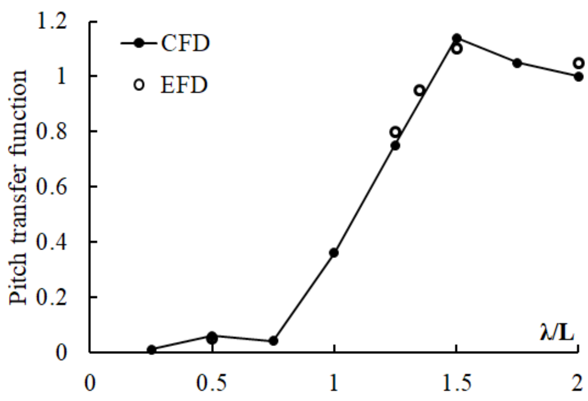


Figure 5. Heave transfer coefficient.

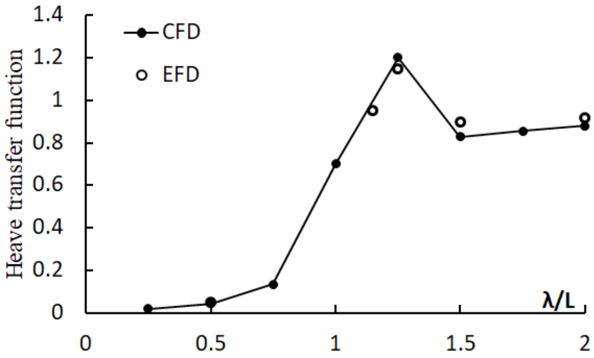


Figure 6. Pitch transfer function.

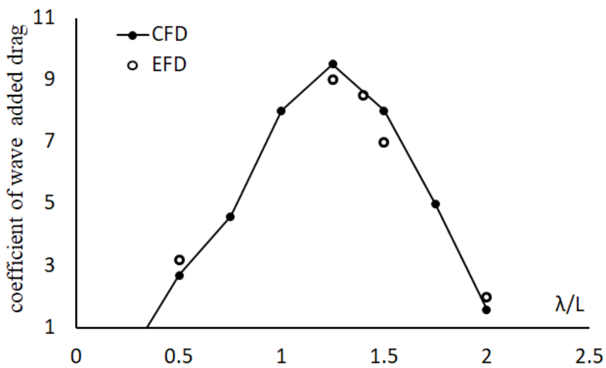


Figure 7. Wave drag coefficient.

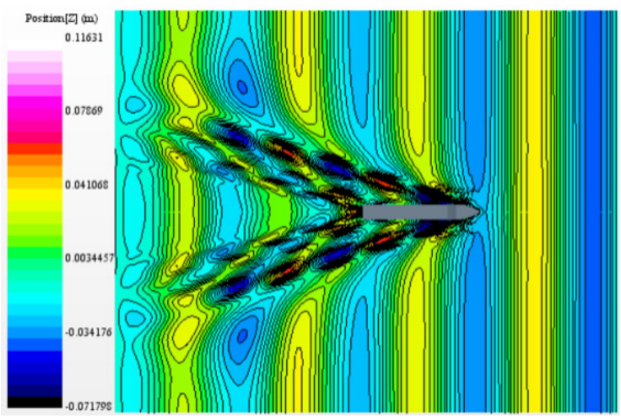


Figure 8. Waveform of interface between water and air (Fn = 0.26, λ/L = 1.0).

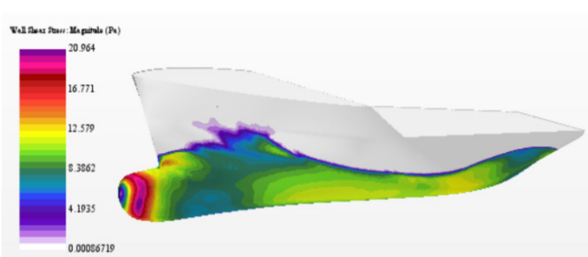


Figure 9. Change of hull shear stress over a period of time (Fn = 0.26, λ/L = 1.0).

4. Calculation of Motion Response of Fishing Boat

The wave resistance and body responses of high-speed fishing boats sailing in waves are calculated. Figure 10 shows the fishing boat's geometric model. And the main dimensions and hull form parameters are shown in Table 3.

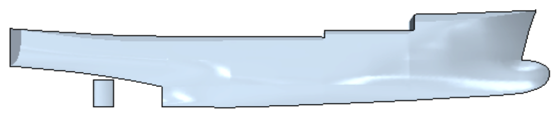


Figure 10. Geometric model of the fishing vessel.

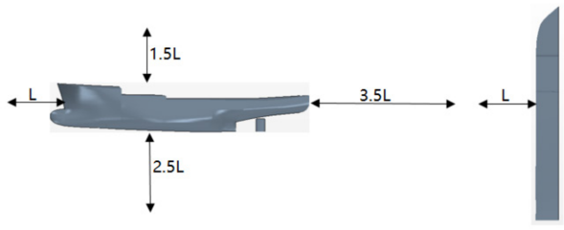
Table 3. The fishing vessel's main dimensions and hull form parameters.

Parameter	**Full-scale ship**	**Model**	**Unit**
Length between perpendiculars (L_{pp})	34.5	4.8	m
Draft (d)	2.5	0.35	m
Moulded width (B)	7.6	1.06	m
Square coefficient (C_B)	0.597	0.597	-
Displacement (Δ)	425	1.45	t
Wet surface area (S)	324	6.27	m^2
Design speed	35	13	kn

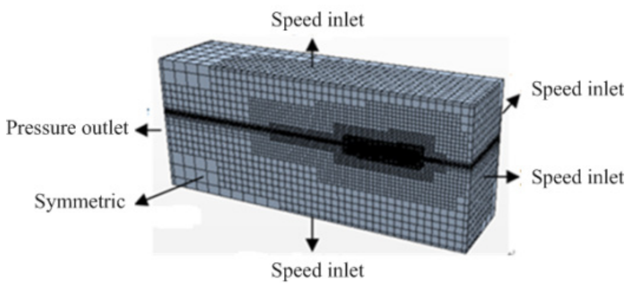
4.1 Calculation Domain and Boundary Conditions

According to the symmetry of the hull, it can be assumed that the flow field is also symmetrical in the numerical simulation, and the symmetry plane is the X-Z plane. Considering the parameters such as wavelength, period and wave height of simulated linear waves, taking half of the hull as the calculation domain can effectively improve the calculation speed. Taking the calculation range of 4.5 L×2.0 L×2.5 L (where L is the captain and the unit is m) as the whole calculation domain, that is, the numerical simulation research object. The distance between the bow and the pool entrance is L, and the simulated water depth is 1.5 L. The specific dimensions are shown in Figure 11. The upper part of the computational domain is air and the lower part is water.

The boundary setting of the velocity inlet is applied to the front surface, the upper surface and the lower surface of the numerical simulation wave pool respectively, and the inflow velocity is added to the boundary of the front surface, which is the velocity of the vessel. Attach the pressure outlet parameter to the rear surface. Attach a rigid surface (wall) parameter to the surface of the boat. Finally, the calculation domain is set to be symmetric on the boundary of the middle longitudinal profile and its opposite sides.



(a)



(b)

Figure 11. Calculation domain and boundary conditions.

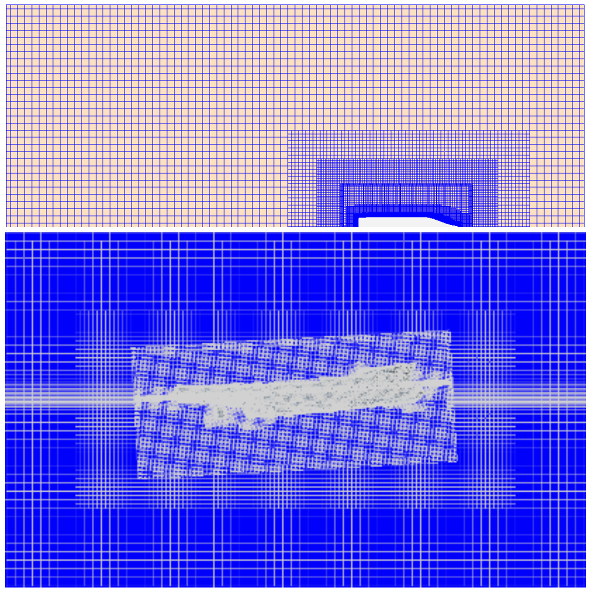


Figure 12. Grid division of free surface and longitudinal section.

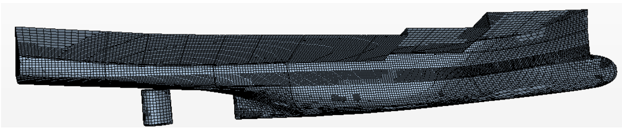


Figure 13. Hull grid division.

4.2 Meshing

Meshing is an essential part of the numerical simulation process. If you change the density and form of the grid, it will change the overall simulation time and the judgment of the results. Therefore, only by grasping the effect of the grid can you control the accuracy and reliability of the calculation results. In this paper, the embedded grid technology is applied in the commercial software STAR-CCM+, and static and dynamic grids are established. As to better analyze the ship's trajectory and sway on waves. Among them, static grids are sparsely drawn, and dynamic grids can be densely drawn with encrypted grids. Overlap and background grid junction should be excessive according to a constant ratio. The interface between air and water must be no less than 80 grilles in the wavelength distance and no less than 20 gratings in the peak-to-trough range. Considering the machine configuration and simulation time, the total number of grids finally determined is 1.85 million. Figure 12 shows the grid near the free surface. As can be seen from the figure, the closer to the hull, the dense the grid, and the farther away from the hull, the more sparse the grid. Figure 13 shows the size and shape of the hull surface grid. And grid encryption is needed at the bow and stern.

4.3 Grid Independence Check

Mesh number has a great impact on the calculation results. The number of grids is too large, which wastes computing resources, is too small, and the results are inaccurate. As a result, it is essential to find a number of grids appropriately. In this paper, five types of grids are calculated respectively, and the calculation grid with less influence on the calculation results due to the increase of grid is obtained. Future calculations are based on this grid. The calculation results are shown in Figure 14.

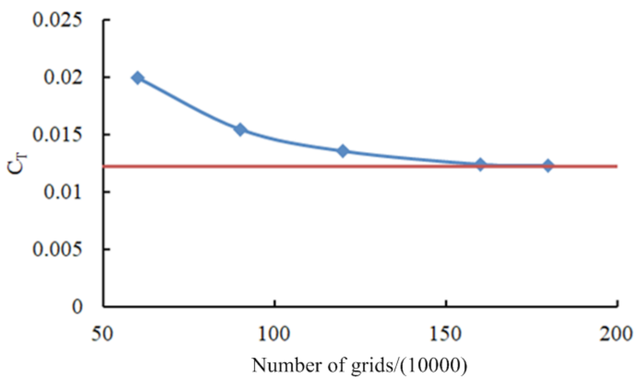


Figure 14. Grid independence.

4.4 Calculation Conditions of Wave Drag Increase

This paper mainly simulates the motion law of fishing boats under different wavelength length ratios and different wave steepness. Take the wavelength to length ratio: λ/L=0.75, λ/L=1.00, λ/L=1.25, λ/L=0.50, λ/L=7.75, λ/L=2.00; and wave steepness: 0.0175, 0.035, 0.0775, 0.0875 as the calculation conditions. The volume fraction of fishing boats is shown in Figure 15.

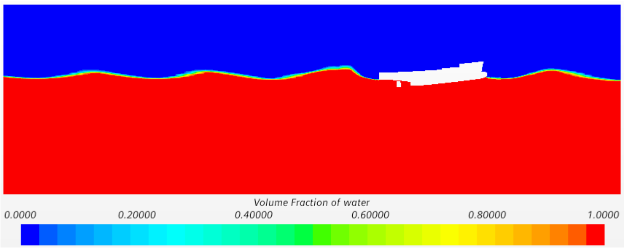


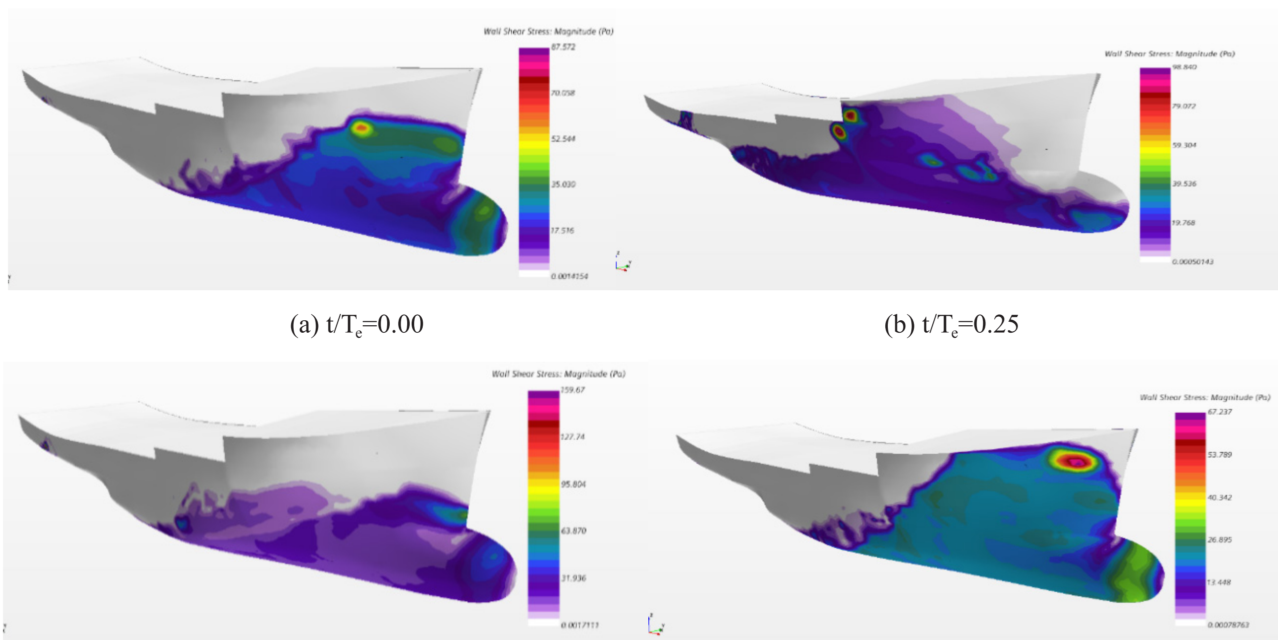
Figure 15. Volume fraction of the fishing vessel.

4.5 Analysis of Simulation Results

Figure 16 shows the relationship between the shear stresses received by the fishing boat hull over a period of time. It can be seen from the figure that the hull shear stress will change continuously with the wave peak and its steepness, especially the bow will bear huge shear stress in 1/4-1/2 cycle, because the bow is located at the wave peak position at this time, and there will be phenomena such as burying the bow or wave on the deck.

Figure 17 shows the changing relationship of the free surface of the hull over a period of time. It can be seen from the figure that the change of draught at the bow and both sides of the hull can clearly show severe heave movements and pitch movements. In addition, waves appeared on the deck. The severe pitching motion may cause the bulbous nose to constantly enter and exit the water surface, resulting in a loud bang on the head, which will worsen the seakeeping of the ship.

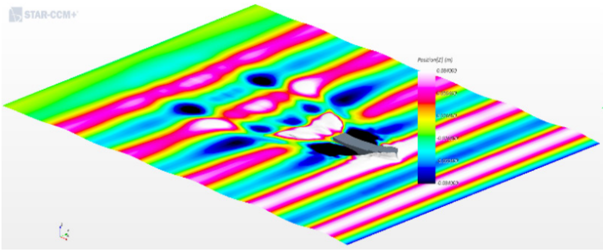
Figure 18, Figure 19 and Figure 20 are the comparisons of the CFD simulation results of the heave, pitch transfer function and wave resistance coefficient of fishing vessels using the slice theory and the panel method respectively. It can be seen from the figure that the calculation curve trend of the three methods is basically the same, and they can well predict the relationship between heave, pitch and wave resistance with the increase of wavelength-to-length ratio. The accuracy of the CFD calculation method has been confirmed by engineering practice, so the CFD simulation results should still prevail in the absence of test values. In addition, the heaving and pitching relationships of the fishing vessel under different wave steepness are also studied. As can be seen from Figure 21, the heave of the ship increases slowly and gradually with the increase of wave steepness. In contrast, the pitching of a ship increases rapidly and gradually with the steep waves.



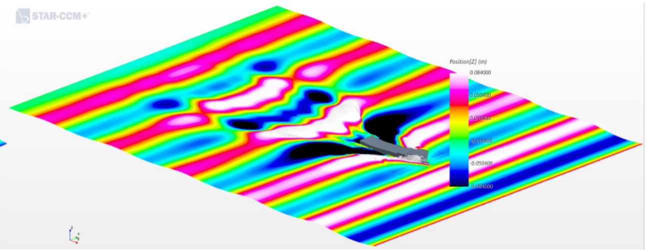
(a) t/T_e=0.00 (b) t/T_e=0.25

(c) t/T_e=0.50 (d) t/T_e=0.75

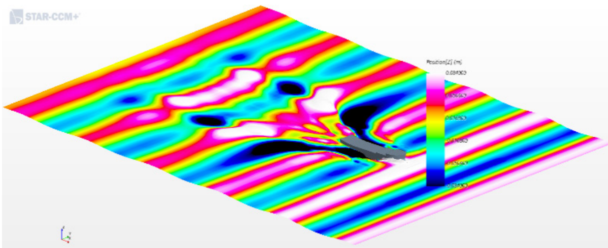
Figure 16. Change of hull shear stress over a period of time (Fn = 0.28, λ/L = 1.0).



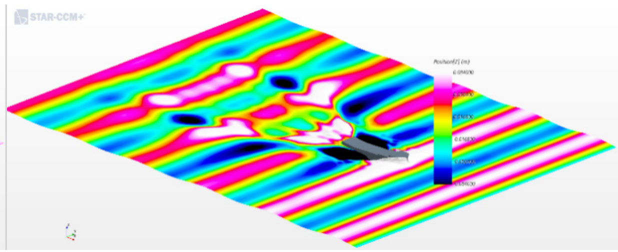
(a) t/T_e=0.00



(b) t/T_e=0.25



(c) t/T_e=0.50



(d) t/T_e=0.75

Figure 17. Waveform of interface between water and air in one cycle (Fn = 0.28, λ/L = 1.0).

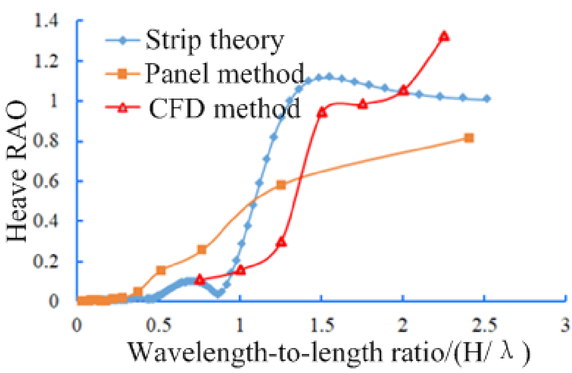


Figure 18. The heave transfer coefficient.

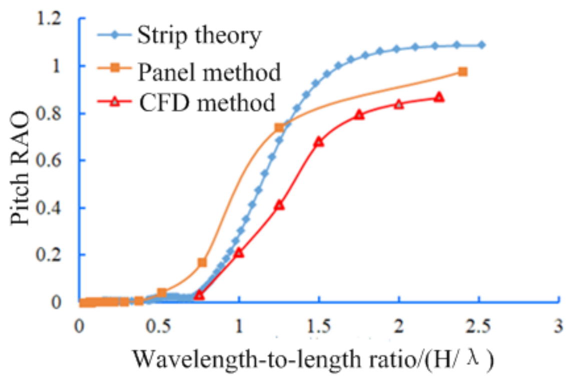


Figure 19. The pitch transfer function.

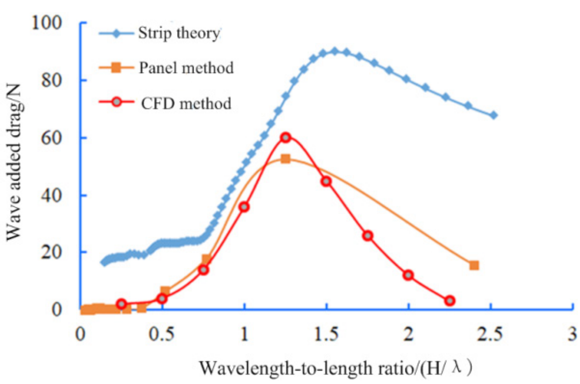


Figure 20. Wave resistance coefficient.

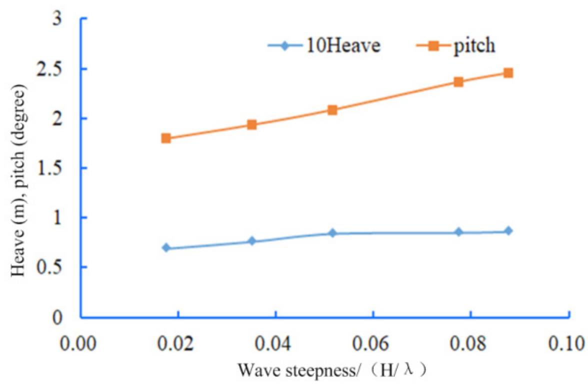


Figure 21. The heaving and pitching values of the fishing vessel under different wave steepness.

5. Conclusions

Based on the CFD method, the commercial CFD software STAR-CCM+ is used to study the resistance and motion response of high-speed fishing boats in waves. The first-order Stokes wave numerical flume is established to simulate the wave resistance, heave and pitch motion response of fishing vessels under the condition of a wavelength length ratio of 0.75 to 2.25. The shape of the Kelvin-free surface wave system is reproduced, and the relationship and reason for the change of the hull surface shear stress are analyzed. Finally, the results of CFD numerical simulation are compared with those of strip theory and panel method, which shows that the CFD method has advantages in simulating ship motion and resistance.

Conflict of Interest

There is no conflict of interest.

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EDITORIAL

Harvesting Offshore Renewable Energy an Important Challenge for the European Coastal Environment

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In the last decades significant changes in the climate are noticed and it becomes obvious that these dynamics are strongly influenced by recent human development. From this perspective, there is an increasing concern regarding the possible evolution of the climate and various possible scenarios have been designed and analysed. Thus, in 2014 the Intergovernmental Panel on Climate Change (IPCC) adopted the Fifth Assessment Report, where the concept of Representative Concentration Pathway (RCP) was introduced for climate modelling. This is a greenhouse gas concentration trajectory labelled after the expected values of the radiative forcing by the end of 2100.

However, the last years' climate developments showed that even the worst scenarios can be exceeded by reality, and various chain effects may occur having locally much more significant impacts than those indicated by the RCP scenarios. Under such circumstances, it becomes obvious that the RCP approach should be completed somehow, and that is why a new and more complex concept has been defined in 2021, in the context of the Sixth Assessment Report of IPCC. This is called the Shared Socioeconomic Pathway (SSP) and provides a holistic picture of climate change in the general context of society development.

A real race started for decarbonisation and to follow the green road in a more consistent way. Almost three-quarters of the greenhouse emissions are generated by the energy sector, while there is worldwide an increasing

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energy demand [1]. From this perspective, it becomes clear for many responsible factors all over the world that rapid and effective measures have to be taken in replacing conventional energy sources based on fossil-fuelled with green energy. Following this trend, the European Union (EU) adopted 2019 the European Green Deal (EGD), which draws the most significant directions to be taken by the EU for rapid and effective decarbonisation of the energy sector [2].

While the land is almost saturated as regards renewable energy extraction, there are large spaces in the marine environment and it is available a huge green energy potential. From this perspective, special attention is paid to Offshore Renewable Energy (ORE). While offshore energy is used to refer to all sources of energy that can be extracted from the ocean, including both renewable sources and fossil-based (for example gas and oil), ORE refers only to the sources of renewable energy that can be extracted from the marine environment. This includes wind, waves, tides, currents, thermal and salinity gradients, floating solar panels and algae-based biofuels. Ocean energy (OE) includes waves, tides and currents, and thermal and salinity.

According to EGD, very ambitious ORE targets are established for 2050. This implies for offshore wind (OW) an installed capacity of 300 GW, a 25 times enhancement in relationship with 2021. The EU target for OE is 40 GW, and since the basis is quite low (13 MW), this means a more than 3000 times enhancement in relationship with 2021. Such very challenging targets for a 30-year time window imply both large geographical extensions as well as significant technological advances.

Some considerations concerning the existent resources and the expected future renewable energy potential in the European coastal environment will be presented next, highlighting also the environmental and technological challenges that have to be faced in the harsh marine environment in the context of climate change.

The northern seas of Europe, the Baltic and North Seas, represent already reliable ORE sources with almost 60 wind farms operating there. Actually, the Baltic Sea is the pioneer in its relationship with offshore renewable energy extraction, since Denmark installed there in 1991 the first offshore wind farm in the world. Baltic Sea has a significant wind power potential and the climate scenarios indicate a slight enhancement in the near future of the average wind energy. The most significant wind power potential is noticed in the North Sea, where average wind power values higher than 1000 W/m^2 are characteristic of large geographical spaces [3]. Furthermore, the climate scenarios indicate that a significant enhancement of wind power is expected in the future with the tendency of the energy peak to move from the north-eastern to the north-western side of the sea.

A very resourceful marine area is represented by the western European coastal environment, where some tidal power plants are already operational and others are currently at the proposal stage together with power plants based on salinity gradients. In this western side of the continent, the Iberian coastal environment represents a significant nearshore from the point of view of ORE potential and of the resources' complementary [4]. This includes wind, wave, tide, and offshore solar energy.

An area with high unexploited potential from the ORE point of view is represented by the Mediterranean Sea, where the first offshore wind farm project became operational in 2022. Several studies [5] indicate hot spots, from the point of view of the wind energy potential, large geographical spaces from the Mediterranean Sea, such as the Gulf of Lion, the Aegean Sea and the southeast of the Iberian nearshore, where average wind power densities higher than 800 W/m^2 are characteristic. Furthermore, the climate projections indicate that in these areas the average wind and solar power is not expected to decrease. As regards the Black Sea, its western side is more energetic and it has very similar characteristics to the Mediterranean Sea.

Although harvesting wind energy is based on mature technologies, there are still expected significant advances. The largest wind turbine in the world, with a rated power of 16 MW, is expected to become fully operational in 2026, and further on the race to the 20 MW wind turbines seems to face no significant obstacle. An emerging technology is related to floating solar panels, which are expected to have a very rapid development in the near future and this development will require significant challenges from the point of view of developing sustainable marine structures.

Conflict of Interest

There is no conflict of interest.

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ARTICLE

Environmental Assessment of Coastal Sand Mining Using Proposed DPSIR Criteria: A Case of Hai Phong

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ABSTRACT

The environmental impact of coastal sand mining activities in Hai Phong city was assessed using ten proposed sustainable criteria for socio-economic development, and ecological and environmental protection. These ten criteria were developed by the analysis of the Dynamics-Pressure-State-Impact-Response (DPSIR) framework, including one driver and pressure criterion (D and P), seven status and impact criteria (S and I), and two response criteria (R). Each criterion is quantified according to five specific evaluation criteria corresponding to the evaluation score from 1 to 5. The results of the ten criterion application for environmental impact assessment of coastal mining Hai Phong by weighting show that the areas with economic activities, benthic biodiversity, and coastal ecosystems are most negatively impacted (score 4/5 and 3.5/5). Other subjects suffer low to moderate impacts (score 1/5 to 3/5). The environmental impact of sand mining (2015-2020) is generally moderate (score ranging from 2/5 to 3/5). The set of adjusted criteria can be applied to similar activities in coastal provinces and cities in Vietnam.

1. Introduction

Environmental assessment is by law required for all development projects in Vietnam, including coastal and marine projects such as sand minings that take place frequently in estuaries along the coast of Vietnam [1]. Coastal sand mining directly has impacts on ecosystems and water quality at mining sites and surrounding areas. In many cases, these impacts are seriously negative on benthic fauna and flora [1-8]. Potential environmental impacts

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on ecosystems and environmental qualities need criteria to rate their levels that often serve coastal sustainable management [9,10]. For specific activities such as coastal sand mining, the proposed criteria focus on assessing their impact on marine ecosystems and water quality at the extraction sites. For years, the criteria have been developed and used over the world [9-13] and in Vietnam for many fields, including environmental assessment as indicators [9,11-14]. In the marine environmental study towards sustainable development in Vietnam, criteria, indicators and indices are developed for assessing the quality of marine environments, marine ecosystems and human activities, and natural processes that affect the marine environment and ecology [9,11,15,16]. A quantitative approach to assessing the impact of sand mining activities in the coastal area of Hai Phong follows the DPSIR (Driver-Pressure-State-Impact-Response) framework that is commonly applied in environmental fields [9,14,17,18]. Accordingly, the criteria for assessing the environmental impact of these activities on the environment and ecosystems in the coastal area are researched, proposed and applied in specific conditions and in the period 2015-2020.

The coastal area of Hai Phong is typical to study the interaction between human development activities and the natural environment due to the diversity of development activities as well as the natural value exploitation versus its conservation. The pressures on marine resources and the environment in this coastal area have questioned effective and reasonable management, exploitation, and use to serve development needs while still ensuring environmental protection goals. In the current issues related to resource management and the environment in Hai Phong, the problem of sustainable management of sand mining activities in the coastal area has emerged. This study focuses on proposing criteria and using these ones for the environmental assessment of coastal sand mining to serve sustainable management in coastal Hai Phong.

2. Methods and Materials

2.1 Study Area

Located in the coastal area of Vietnam's Northeast region, Hai Phong city is a place with many favorable conditions for socio-economic development. Key economic sectors of coastal Hai Phong include maritime shipping and ports with the largest seaport system in the North and the gateway to the sea of the Northern provinces of Vietnam, marine tourism with sand beaches and land and sea sceneries and urbanization associated, aquaculture and agriculture, mining of constructional materials including sands. Coastal Hai Phong is also known for its rich marine resources, many endemic species, and high economic value living resources and high biodiversity, particularly in Cat Ba Biosphere Reserve listed by UNESCO (2004). In recent years, due to fast and intensive economic development, the demand for the exploitation and use of natural resources is increasing, especially the demand for materials of construction to expand coastal areas and urbanization.

The study area in coastal Hai Phong is bordering with the mainland crossing the ecosystems of tidal flats and beaches in the North, Cat Ba Biosphere Reserve and Ha Long Natural Heritage that possess valuable marine ecosystems like corals and mangroves in the East, open waters with low biodiversity of the soft bottom ecosystem of the Tonkin Gulf in the South, and coastal Thai Binh province with the ecosystems of mangroves and tidal flats in the West. Two main seasons including a dry one (October to April) and a rainy one (May to September) within a year control hydrometeorological conditions of the area. Also, in the rainy season, the area is directly or indirectly attacked by one to three typhoons that often make some sudden changes to the coastline, intertidal zone and seabed, etc. There are 5 rivers (Bach Dang, Cam, Lach Tray, Van Uc, and Thai Binh) discharging water and sediments into the area through their river mouths. Diurnal tide with a tidal range of about 4 m and tidal currents dominate the coastal waters of Hai Phong. Seabed and intertidal zone in the area are mostly flat and covered with sandy and muddy sediments at depths ranging from 0 m to 15 m [1]. The study area annually receives tens of million cubic meters of mud and sand from the rivers. The sedimentation over a long time has formed sand mines in the area outside the river mouths of Nam Trieu, Lach Tray, and Van Uc-Thai Binh [1].

In the 2015-2020 Master Plan for Hai Phong socio-economic development, the coastal reclamation for urbanization, tourist resort construction, and new seaport facility development associated with industrial zones, the amount of sand for landfill leveling was estimated at 251 million cubic meters and increasing in the period 2020-2030 [1]. The huge demand for landfill sand mining in recent years has also made sand mining intensive in this coastal estuary area. In addition to the economic benefits, these activities can cause many environmental consequences, especially in the coming years when the demand for sand mining is further boosted. According to the City's Adjustment Scheme "*Planning for exploration, exploitation and use of minerals in the city until 2020, with a vision to 2030*", the areas planned to exploit sands for landfill leveling are 8.2 thousand hectares, with reserves of about 142 million m^3. The areas that are permitted to explore and exploit sand as construction materials in Hai Phong city are mainly located outside the estuaries of Van Uc and Nam Trieu-Lach Tray, South Cat Hai district, along the coast of Do Son peninsular. As of August 2019, 22 sand mining licenses were issued (of 18 enterprises) and are still valid. The total area licensed for sand mining in Hai Phong city is 1953.1 ha with a total exploiting reserve of approximately 81.5 million m^3. The sand mining licensed projects are concentrated mainly in the Southeast estuaries of Van Uc, Lach Tray, Lach Huyen and Nam Trieu-Bach Dang (Figure 1). These sand mining projects vary in size. The area of sand mines averages about 90.1 ha, the largest at 99.9 ha and the smallest at 8.6 ha. These sand mines have different reserves with the largest of 5.2 million m^3, the smallest of about 0.8 million m^3 and the average of 3.88 million m^3. The average depth after mining these sand mines increases to 4.3 m at the sand mining sites, a maximum of 7.2 m and a minimum of 2.1 m. The mining period of the licensed mines is from 7 to 29 years. So far, the annual exploitation volume of licensed projects totals 9.3 million m^3. The annual exploitation duration of sand mines lasts about 150-200 days, commonly about 180 days and 8 hours per day. The relative position analysis of these sites shows their locations to sensitive areas as follows: To Van Uc river mouth, the nearest is 2.7 km from the mangrove forest, and some mining parts overlap with the clam culturing areas; to Cat Ba Biosphere Reserve, the nearest is about 4 km.

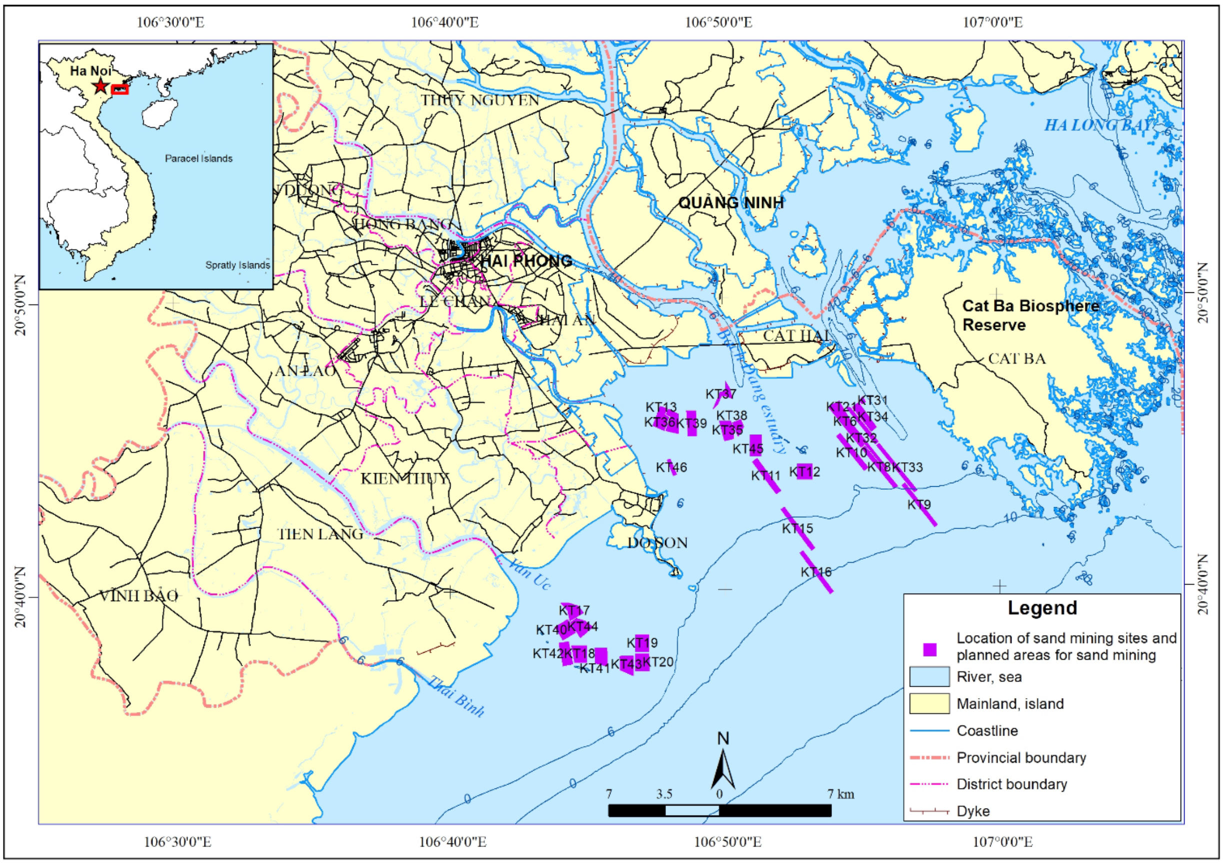


Figure 1. Sites and planned areas for sand mining in coastal Hai Phong.

2.2 Methods

The two basic methods employed in this study include the DPSIR framework analysis and the Delphi matrix. The DPSIR has been applied in many studies around the world in different fields and is effective in analyzing and evaluating effects and interactions with each other among the elements in the framework [9,15,18]. In this study, driving forces are the factors promoting coastal sand mining, leading to changes in the coastal marine environment. These factors may include the ones that directly or indirectly trigger mining sands. These factors can be economic, social or natural ones that have positive or negative effects, causing changes in the quality of the marine environment and impacts on the marine ecosystem. For example, the increasing sand demand of Hai Phong city for landfill leveling and construction in coastal urbanization and seaport expansion is a direct factor triggering sand mining activities, and the global need for sand as minerals for industries and for construction materials belongs to indirect factors related to sand mining. From a local perspective, the driving force behind increasing sand mining projects comes from the city's socio-economic development needs, especially in the field of leveling and infrastructure construction. Besides, the impetus comes from the increasing demand for sand for leveling and construction in the world. The driving force causes pressure on the coastal resources of Hai Phong through the increase in the opening of sand mines and the increase in illegal and over-exploiting activities. Through the assessment of the current status of the study area, environmental and socio-economic issues in sand mining places determine the environmental impacts of the activities, analyze, evaluate, and propose solutions to minimize negative impacts, promoting positive factors to meet the goal of sustainable development in coastal areas.

The Delphi matrix method [19] is mainly applied when developing and analyzing the criteria to assess the impact of sand mining on the coastal environment of Hai Phong. The criteria went through three steps. The first step involved a group of experts conducting the study in the period 2015-2020 (8 experts), the second step was conducted with a questionnaire after synthesizing and classifying criteria according to the results of the first step and consulting experts in the fields of environment, ecology, oceanography, environmental and resource management (35 people). The third step took place with the results of the second step by qualitative analysis (expert opinion) and quantitative analysis (expert consensus level), and 50 consulting experts. The criteria were classified following three pillars of sustainable development and associated with a rating scale from 1 to 5 points showing the importance of each selected criterion. Then the criteria were gathered, statistically processed, and selected based on the consensus level according to the parameter standard description in statistical analysis. Ten selected criteria were used to assess the impact of sand mining activities on the environment and ecosystems in the coastal area of Hai Phong. To evaluate the reliability of the statistical evaluation, crossbach's alpha coefficient was used.

Besides, the biodiversity index or Shannon-Wiener index (H') is employed to measure sand mining's impact on the soft-bottom ecosystem. The biodiversity index is a way to measure the diversity of species in a community. The index H' is calculated as follows [20,21]:

$$H' = \sum_{i=1}^{s} Pi\ lnPi$$

where P_i is the proportion of individuals found in the i^{th} species and ln denotes natural logarithm.

Values of Shannon index for real communities are often found to fall between 1.5 and 3.5. The higher the value of H', the higher the diversity of species in a particular community.

2.3 Materials

Materials used for the study are mainly from the results of the scientific research project at Hai Phong city level "Research to assess the impact of sand mining activities on the environment of coastal estuaries in Hai Phong" implemented by the Institute of Marine Environment and Resources, 2017-2019. In addition, other information and documents of environmental impact assessment reports of Hai Phong coastal sand mining projects, the project "General assessment of the current status of coastal areas of Hai Phong city" (2013) and the project "Solutions for environmental contrasts in coastal areas" (2009-2013) were used.

3. Results and Discussions

3.1 DPSIR Analysis of Sand Mining Activities to the Environment

The DPSIR framework for analyzing the environmental impact of sand mining activities in the Hai Phong coast (Figure 2) shows the main aspects of each component in the framework and the relationship between the components.

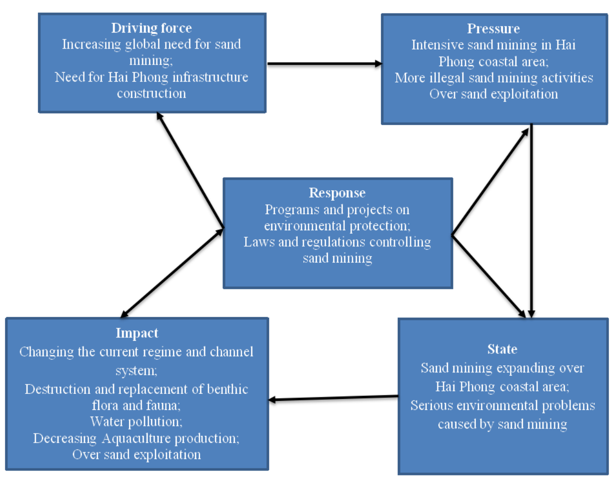


Figure 2. Applying the DPSIR to assess the impact of sand mining on the environment in the coastal Hai Phong.

In addition to the environmental and ecological impacts in the area, the impact of sand mining on socio-economic activities in this coastal area is also a prominent issue recently, which is the conflict between sand mining with shellfish farming. Sand extraction actors directly conflict with clam farmers because of the overlap in marine and intertidal exploiting areas. These are the most obvious and serious consequences of sand mining even though most mining projects have been licensed. However, the issues of zoning, planning, and allocating land and water surface to shellfish farming households have not been implemented yet.

3.2 Proposed Criteria to Assess the Impact of Sand Mining Activities on the Environment

Based on the DPSIR analysis, synthesizing relevant documents and consulting experts on the appropriateness, ten criteria to evaluate the impact of sand mining activities on the environment in the Hai Phong coastal area have been proposed and classified into 3 groups: 1) Criteria of driver and pressure of sand mining activities; 2) Criteria of current status and impacts of sand mining activities; 3) Criteria for the response.

Criteria of driver and pressure

Criterion 1: Local demand for sand mining shows the driving forces and pressures on sand mining. This criterion is evaluated with five levels based on the output/year in comparison with the mining plan. Mining production is divided into five grades (no sand mining, mining less than 30% of the output plan, mining 30%-50% of the output plan, mining > 50%-70% of the output plan, and mining over 70% of the output plan), corresponding to five impact levels (1—no impact to 5—very high impact) respectively.

Criteria of the status and the impacts of sand mining

Criterion 2: The seabed topography in the sand mining area is used to evaluate the natural compensation possibility of seabed topography after sand mining. This is related to current conditions, waves, seabed morphology [22], and the capacity to backfill the bottom topography with sand (or other materials). Then for the comprehensive result of the compensation capacity, the bathymetry changing is an indicator. As such, the depth of sand mining is taken into account and divided into five grades (deeper 30 m, 30 to > 20 m, 20 to > 10 m, 10 to 6 m, and < 6 m) corresponding to five impact levels (1—no impact to 5—very high impact) respectively.

Criterion 3: Suspended sediment dispersion in the water environment is to assess the dispersion of suspended sediments from mining sites to the surrounding environment with its values. Spreading suspended particles to highly significant subjects (natural and socio-economic) will have negative impacts on them. The higher concentration of suspended sediment is above the allowable limit (issued in Vietnam Regulations for Environmental Protection—QCVN), the more serious the negative impacts on the subjects. As such, the impacting dispersion includes five categories (not spreading to protected areas, important ecosystems, breeding grounds, spawning grounds, tourist areas, aquaculture; dispersing to conservation areas, important ecosystems, breeding grounds, spawning grounds, tourist areas, aquaculture but not exceeding the allowable limit; dispersing to conservation areas, ecosystems, breeding grounds, spawning grounds, tourist areas, aquaculture is approximately the allowable limit; dispersing to conservation areas, ecosystems, breeding grounds, spawning grounds, tourist areas, aquaculture with concentrations up to 3 times exceeding the allowable limit; dispersing to conservation areas, ecosystems, breeding grounds, spawning grounds, tourist areas, aquaculture with concentrations higher than 3 times exceeding the allowable limit). These categories correspond with five impact levels (1—no impact to 5—very high impact) respectively.

Criterion 4: Distance from the location of sand mining to socio-economic entities is to assess varying degrees of sand mining impacts on coastal residential areas, tourist beaches, historical and cultural sites, and aquaculture areas. The impacts may include coastal water pollution, changing the current regime and channel system, and over-sand exploitation leading to erosion at tourist beaches and coastal resident areas, decreasing coastal aquaculture production (shellfish farming). The degree of impact largely depends on the distance between the sand mining activities and the socio-economic groups. Generally, sand mining makes more serious adverse impacts on socio-economic groups when it takes place closer to the groups. Then five different recommended distances relevant to five impact levels (1—no impact to 5—very high impact) respectively include farther 15 km, 15 to > 10 km, 10 to > 5 km, 5-1 km, and < 1 km.

Criterion 5: Biodiversity of benthic fauna uses the biodiversity index (H') measured before and after sand mining takes place to assess the impacts on benthic organisms as a basis for assessing the impact on the soft bottom ecosystem. The changes in the seabed environment cause changes in benthic fauna and flora. Therefore, the difference between H' before and after mining indicates the impact levels. Based on the biodiversity baseline in the study area, five H' value intervals recommended relevant to five impact levels (1—no impact to 5—very high impact) respectively include > 5, 5 to > 3, 3 to > 2, 2-1, and < 1.

Criterion 6: Distance from the location of sand

mining to the coastal ecosystem and the national park is for assessment of sand mining that causes increased turbidity and re-dispersal of deposited pollutants. The further away from sand mining activities take place, the less the impact of these activities. Similar to Criterion 4, five recommended distances relevant to five impact levels (1—no impact to 5—very high impact) respectively include father 15 km, 15 to > 10 km, 10 to > 5 km, 5-1 km, and < 1 km.

Criterion 7: Distance from the location of sand mining to fishing grounds and nursery grounds is applied to assess the impacts of sand mining activities on these grounds. This criterion can be merged with Criterion 6 in some marine areas with the grounds merging with the coastal ecosystem. The further away sand mining takes place, the less the impact of these activities. Similar to Criterion 4, five distances relevant to five impact levels (1—no impact to 5—very high impact) respectively include father 15 km, 15 to > 10 km, 10 to > 5 km, 5-1 km, and < 1 km.

Criterion 8**:** ***Quality*** **of** ***seawater environment*** is used to periodically assess its environmental status in and around areas with sand mining activities. The impact levels in score range from 1 to 5 for each indicator according to the water pollution classification under Circular No. 17/2011/TT-BTNMT (Vietnam Regulations for Environmental Protection—QCVN). The average combined results of each evaluated parameter show the criterion impact levels (Table 1).

Table 1. Indicators for assessing the impact levels related to sea water quality.

Water quality indicators	**Content**	**Negative impact level (score 1-5)**
Total suspended solids (TSS) (mg/L)	Less than the allowable limit according to QCVN	1
	Approximate allowable limit according to QCVN	2
	1-3 times higher than the allowable limit	3
	>3-5 times higher than the allowable limit	4
	>5 times higher than the allowable limit	5
Dissolved Oxygen (DO) (mg/L)	Within the allowable limit according to QCVN	1
	Not within the allowable limit	5
COD ($KMnO_4$) (mg/L)	Less than the allowable limit according to QCVN	1
	Approximate allowable limit according to QCVN	2
	1-3 times higher than the allowable limit	3
	>3-5 times higher than the allowable limit	4
	>5 times higher than the allowable limit	5
Ammonium (NH_4^+) (mg/L)	Less than the allowable limit according to QCVN	1
	Approximate allowable limit according to QCVN	2
	1-3 times higher than the allowable limit	3
	>3-5 times higher than the allowable limit	4
	>5 times higher than the allowable limit	5
Phosphate (PO_4) (mg/L)	Less than the allowable limit according to QCVN	1
	Approximate allowable limit according to QCVN	2
	1-3 times higher than the allowable limit	3
	>3-5 times higher than the allowable limit	4
	>5 times higher than the allowable limit	5
Arsenic (As) (mg/L)	Less than the allowable limit according to QCVN	1
	Approximate allowable limit according to QCVN	2
	1-3 times higher than the allowable limit	3
	>3-5 times higher than the allowable limit	4
	>5 times higher than the allowable limit	5
Quality of sea water environment	(Average of water quality indicators)	(ranges from 1-5)

Criteria of response

Criterion 9: Effectiveness of policy on sand mining management involves assessing the role of state and local management of sand mining activities that negatively impact the natural environment, socio-economic, and ecosystem. The effectiveness of policies including laws and regulations issued by governments (central and local) related to coastal sand mining possibly decreases the negative impacts and vice versa. Assessment of real impact and possible impact on the environment supports policymakers to judge the efficiency of the policy periodically. The more effective the environmental policy is, the lower the impact of these activities. This positive criterion is in contrast to the criteria of drivers and pressures. The criterion ranges from "very effective" to "ineffective" (very highly effective, highly effective, averagely effective, low effective, and ineffective) corresponding with 5 points (1—very effective, 5—ineffective) of impact levels.

Criterion 10: Marine environmental protection programs and projects implemented in the city are to evaluate the effectiveness of environmental protection programs and projects in mitigating the negative impacts of sand mining activities in Hai Phong city. Similar to Criterion 9, this is a positive criterion, in contrast to the criteria of drivers and pressures. The environmental assessment after completing the programs and projects in a stage and environmental monitoring onward will show the levels of negative impacts from no more impact to no reduced impact. Therefore, the criterion of 5 impact reduction levels (no more impact, reduced to the required level, reduced but not meeting the required level, a bit reduced, not reduced) after completion of programs or projects is in 5 points (1—no more impact, 5—not reduced impact) respectively.

3.3 Assessment of Coastal Mining Impacts on the Environment

An environmental impact assessment of sand mining activities in the coastal waters of Hai Phong with 10 proposed criteria was applied for 30 project areas of sand mining (Figure 1). Criterion 6 and Criterion 7 got the same points because the breeding and spawning grounds are located in the ecosystems of the estuary, coral, and mangroves in the study area.

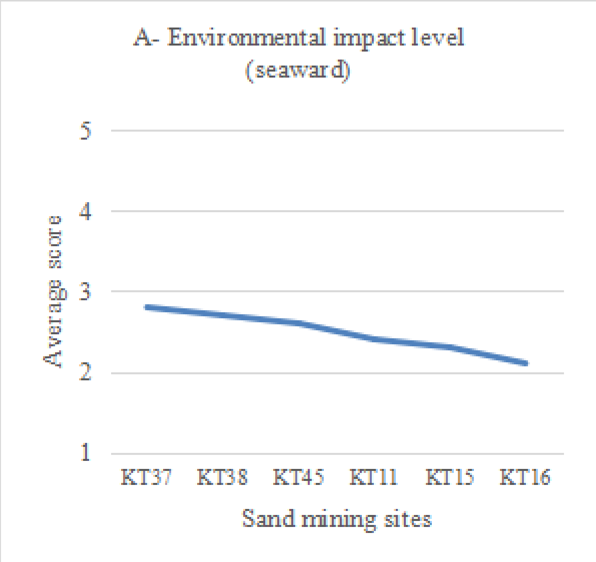
The overall assessment for the entire study area was made based on the average of the evaluation results for all 30 areas. Criteria from 1 to 8 had evaluation scores calculated with data collected in the period 2015-2020. Criteria 9 and 10 were scored by relevant experts who come from environmental agencies of Hai Phong, research institutions and universities located in Hai Phong (e.g. Institute of Marine Environment and Resources, IMER; Research Institute of Marine Fisheries, RIMF; Vietnam Maritime University, VMU; Hai Phong University, etc.), and others having much experiences and information on environmental issues caused by human activities in coastal and marine areas including sand mining. Scores ranged from 1 to 5, corresponding to the impact level from the lowest to the highest (Table 2).

Assessing results show that the impact of coastal sand mining is strongest in areas with economic activities, on biodiversity and benthic organisms (rated score of 4), and coastal ecosystems (rated score of 3.5). The other subjects were affected only at a low to moderate level (rated score from 1 to 3). The trend in environmental impact level shows a decrease from shallow waters close to the coastline (including sandy tidal flats) with dense socio-economic activities and valuable ecosystems like mangroves to deeper ones with low biodiversity (Figure 3A). Also, the low impact level is in the area farther from highly valuable ecosystems like corals, seagrass in Cat Ba Biosphere Reserve (Northeast), and mangroves in Van Uc river mouth (Southwest) (Figure 3B). The overall assessment of the environmental impact of sand mining activities in the study area in the period 2015-2020 is average (rated score of 3).

The results of the environmental impact assessment of sand mining activities in Hai Phong coast are relatively consistent with the evaluations in the "Report on the current state of the coastal area of Hai Phong city" issued by the Sea and Island Division under Hai Phong Department of Natural Resources and Environment (2020) on two groups of criteria: Protection, restoration, and management of ecosystems; Waste management and pollution reduction. Crossbach's alpha coefficient value approaches 0.7. Frequently, Crossbach's alpha benchmark value at 0.7 and higher indicates a reliable measure (Delphi matrix). A coefficient value close to 0.7 is minimally acceptable but not ideal. This study on coastal environmental assessment with proposed DPSIR criteria is a new effort to qualify the impact of sand mining on the environment in Hai Phong particularly and in Vietnam generally. Therefore, the coefficient value near 0.7 can be accepted and indicates sufficiently minimal consistency in data collection for the employed method of Delphi matrix. This also presents the potential to apply the DPSIR criteria for environmental assessment in other fields and regions.

Table 2. Criterion scoring of environmental impact assessment of sand mining activities in coastal waters of Hai Phong (averaging of 50 interviewees).

Mining sites	Criteria														Average score
	1	**2**	**3**	**4**	**5**	**6&7**	**8_TSS**	**8_DO**	**8_COD**	**8_NH4**	**8_PO4**	**8_As**	**9**	**10**	
KT6	2	5	1	4	4	4	3	1	3	1	1	1			2.6
KT8	2	5	1	4	4	3	3	1	3	1	1	1			2.5
KT9	2	4	1	4	4	3	1	1	3	1	1	1			2.3
KT10	2	5	1	4	4	3	3	1	3	1	1	1			2.5
KT11	2	5	1	3	4	3	3	1	3	1	1	1			2.4
KT12	2	5	1	3	4	3	3	1	3	1	1	1			2.4
KT13	2	5	1	4	4	4	3	1	3	3	1	1			2.7
KT15	2	4	1	3	4	3	2	1	3	1	1	1			2.3
KT16	2	3	1	3	4	2	1	1	3	1	1	1			2.1
KT17	2	5	1	4	4	4	3	1	3	3	1	1			2.7
KT19	2	5	1	4	4	3	3	1	3	3	1	1			2.6
KT20	2	5	1	3	4	3	3	1	3	3	1	1			2.6
KT32	3	5	1	4	4	3	3	1	3	1	1	1			2.6
KT33	2	5	1	4	4	4	3	1	3	1	1	1			2.6
KT35	2	5	1	4	4	3	3	1	3	3	1	1	3 (Scored by experts and interviewers)	3 (Scored by experts and interviewers)	2.6
KT39	2	5	1	4	4	4	3	1	3	3	1	1			2.7
KT40	2	5	1	4	4	4	3	1	3	3	1	1			2.7
KT42	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT43	3	5	1	3	4	3	3	1	3	3	1	1			2.6
KT44	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT45	2	5	1	4	4	3	3	1	3	3	1	1			2.6
KT31	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT21	3	5	1	4	4	4	3	1	3	1	1	1			2.6
KT18	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT34	2	5	1	4	4	4	3	1	3	1	1	1			2.6
KT36	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT37	3	5	1	4	4	4	3	1	3	3	1	1			2.8
KT38	3	5	1	4	4	3	3	1	3	3	1	1			2.7
KT41	2	5	1	3	4	3	3	1	3	3	1	1			2.6
KT46	4	5	1	4	4	4	3	1	3	3	1	1			2.9
Averaged score	***2***	***5***	***1***	***4***	***4***	***3.5***	***3***	***1***	***3***	***3***	***1***	***1***	**3**	**3**	



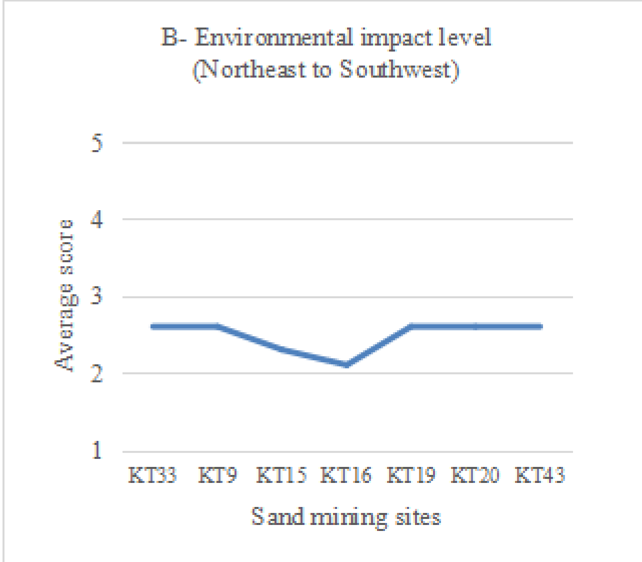


Figure 3. Trends in environmental impact level of sand mining by average scores: A- from coast to open sea; B- along the coast at the depth from 6 m to 10 m.

4. Conclusions

The environmental impact of sand mining activities in the Hai Phong coastal area was fair with a rated score ranging from 2 to 3 among mining sites and stronger (rated score from 3.5 to 4) on the coastal areas of dense economic activities, high biodiversity and benthic organisms, and coastal ecosystems in the stage from 2015 to 2020. Ten proposed criteria are well involved in the management and planning of socio-economic development, conservation, and environmental protection in Hai Phong coastal areas. These criteria can also be applied to assess the environmental impact of similar activities on the coastal areas in cities and provinces in Vietnam with their adjustment. However, to have more reliable assessment results, it is necessary to collect data sets and systematic information, covering both space and time in the area and activities to be assessed. This is also the current limitation when using the criteria in environmental and ecological assessment, especially in coastal and marine areas.

Author Contributions

Tran Dinh Lan conducted the study and wrote this paper. Do Thi Thu Huong developed and analyzed multi-criteria and maps. Do Gia Khanh collected data and statistical analysis of socio-economic data. Nguyen Van Thao analyzed physical and environmental data.

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Conflict of Interest

There is no conflict of interest.

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ARTICLE

The Role of Chittagong Port Authority to Develop Other National Ports in Bangladesh to Provide Maritime Logistics Support in South Asia

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ABSTRACT

Chittagong Port is the principal seaport in Bangladesh that has contributed to the national economy with the opportunity to be a world-class regional port in South Asia. Cooperation among the three national ports Chittagong, Mongla and Payra is essential to do maritime logistics business in the region after serving the nation proudly. Here, Chittagong Port Authority (CPA) has the opportunity to help others in the process of port development for increasing efficiency and productivity by providing financial and technical assistance because of its financial and technical capabilities as a pioneer seaport in the port world. This paper examines the role of CPA to bolster and develop the underutilized Mongla Port and newly established Payra Port, where qualitative research methodology is applied to explore the ways, by which CPA can assist, link and integrate with others effectively, especially in developing the port infrastructure and inland transport networks. In addition, the research found the prospectus of Mongla and Payra to supply port services to the neighbors India, Nepal, and Bhutan as well as serve the South-West part of China with the aim of increasing regional connectivity and promoting international trade in those basically landlocked areas and countries of Asia.

1. Introduction

Chittagong Port is the principal seaport in Bangladesh that has contributed to the national economy with the opportunity to be a world-class regional port in South Asia. Cooperation among the three national ports Chittagong, Mongla and Payra is essential to do maritime logistics business in the region after serving the nation proudly. Here, Chittagong Port Authority (CPA) has the opportunity to help others in the process of port development for increasing efficiency and productivity by providing financial and technical assistance because of its financial and technical capabilities as a pioneer seaport in the port world. Maritime logistics and port connectivity are playing important roles in promoting regional economic

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development that is closely associated with the efficiency and quality of shipping and port activities [1]. Ominously, Bangladeshi seaports are not yet considered efficient by the global standard in terms of technical or non-technically especially operational efficiency, infrastructural bottleneck, backward transport networks, poor information technology usage, financial delay in investment and poor port management [2]. Mention that the strong relationship between the port and port city or city is weakening both in economic and geographical terms [3]. Moreover, a port is the heart of the transport system to interfaces among various transport modes to enhance connectivity to their hinterlands and forelands [1,4]. In essence, port development is required in Bangladesh for facilitating the domestic import-export trade and supporting the South Asian region for economic growth and trade development that will be treated as a maritime transport business.

This paper started with a special discussion on "Country moves with us" where the importance of port facilities for Bangladesh is described and then turned to the next section of research methodology where qualitative research methodology is followed to get the empirical reflection of experts on port management. After that related works of kinds of literature on port performance, competitiveness and governance stated with short literature on South Asian maritime transport system, including Bangladesh's port facilities, intermodal freight transportation and inland transport networks for understanding gaps in the literature for developing ports of Bangladesh for increasing maritime logistics support to South Asia. Furthermore, this research attributed the statement and feelings of the respondents in the qualitative research findings section. Based on the literature review and qualitative research findings, one section was added for analyzing the role of CPA to develop all ports of Bangladesh inspired the next section for creating a regional common platform for transport connectivity. Finally, the paper concluded with the future directions that will help to extract important points for port development in Bangladesh.

Moreover, port authorities have a stake in innovation for improving operations, gaining competitive advantage, achieving and maintaining a 'license to operate', and finally achieving resilience against a changing environment [5]. This paper examines the role of CPA to bolster and develop the underutilized Mongla Port and newly established Payra Port where qualitative research methodology is applied to explore the ways by which CPA can assist, link and integrate with others effectively, especially in developing port infrastructure and inland transport networks. In addition, the research found the prospectus of Mongla and Payra to supply port services to the neighbors India, Nepal and Bhutan as well as serve the South-West part of China with the aim of increasing regional connectivity and promoting international trade in those basically landlocked areas and countries of Asia.

2. Country Moves with Us

Chittagong port has the slogan of "Country Moves with Us" which featured its importance in the national economy and social responsibility to all citizens of Bangladesh. Driven in particular, Bangladesh is moving forward with the performance of Chittagong port inevitably. Most of the import-export trade of Bangladesh is performed by seaports where Chittagong port is managing more than 90% of trade and the country is dependent on the performance of Chittagong port. Brightly, the Chittagong port master plan researched by HPC (Hamburg Port Consultancy) projected the container traffic in 2.7, 4.4, 5.1 and 5.4 million TEUs (Twenty feet Equivalents Units of Containers) for the years 2020, 2025, 2030 and 2040 respectively that will be doubled within the next 20 years [6]. From the research of Kharel [7], it is found that Nepal and Bhutan are striving to get reasonable port access in South Asia where they are paying 42% excess cost with the penalty of a time burden for using the ports of India. Here, they are using the congested and inefficient ports of India, whereas Chittagong and Mongla ports of Bangladesh are potential alternative ports for them. Moreover, freedom of transit is appreciated by all in South Asia, especially for landlocked countries Nepal and Bhutan to access Bangladesh markets and seaports predictably. Furthermore, the opportunity remains for China, India and Myanmar to use the ports of Bangladesh to decrease the transport cost and develop their countries' dark areas that are basically landlocked or undeveloped.

In order to handle all modes of transport, both coming from the sea or hinterland, it is crucial to develop a port in which the speed of handling is set at the highest level [8]. he most important value-added and investment level in port-related manufacturing and logistics support by creating space in the supply chain to show better port performance [9]. If there is no cooperation between the actors in the port community, the assessment of rates on performance could not be generated and may not be useful in the process of port development [10]. In this situation, as a leader and pioneer in port management, CPA has to show the path to other national ports to increase productivity, compete with others and enable maritime transport as a part of port governance in the modern world. To unfold, ports have to serve the nation together where port cooperation is appreciated because the fate of the nation is highly dependent on the import-export trade where the country is moving forward with the best performance of port superciliously.

3. Research Methodology

Social research is a collection of methods and methodologies that needs to apply systematically for producing scientifically based knowledge and it's an exciting process of discovery where persistence, personal integrity, and tolerance for ambiguity are required to complete the research successfully [11]. Preliminary, to analyze of the basic two research questions (*How CPA can play a vital role to develop underutilized Mongla Port and newly established Payra Port? How CPA can assist, link and integrate with others effectively?*), followed the qualitative research methodology of Neuman [11], and followed the field research for taking the interview with people acting in the research area. Finally, qualitative research methodology is applied to get the real thought of the actors who are related to the performance and motion of the Bangladesh port sector. The qualitative process always strives the get new things or innovations from the respondents that will contrast with the literature review and secondary source information appropriately.

Extraordinarily, UNCTAD (United Nations Conference on Trade and Development) published its first research paper on "Port Cooperation" in 1996 where cooperation between ports within the country or region had attributed highly and to date this paper is the great direction for ports in managing their activities by providing or getting helps each other. This paper is the main document in selecting the areas where CPA can work with other national ports for bolsters own capacity and guide others on how to bring the standards like a CPA to attract port users and international traders. In this connection, three major indicators are chosen for this research which are port performance, competitiveness and governance and by increasing the international standard level of those indicators, it is possible to provide maritime logistics support nationally, regionally and internationally.

Furthermore, CPA has to play a vital role to support Mongla and Payra with the aim of developing their capacity based on the literature of UNCTAD [12] and extracting the below types of cooperation in developing the overall port sector of Bangladesh.

1) Institutional. Arrange to support other ports by inspiring governments, international development organizations like ADB (Asian Development Bank), AIIB (Asian Infrastructure Investment Bank), World Bank and others exclusively for capital investment in the port infrastructure, equipment purchase and facilities development.

2) Industrial. Organize other ports and group with international associations like IAPH or regional port association in getting technical assistance and emergency troubleshooting.

3) Commercial. Guide how to negotiate with the international investor for long-term investment in the Bangladesh port sector and show how they will be benefited from this investment gradually.

Overall, in addition to secondary literature review including the UNCTAD [12] research paper, qualitative research methodology was applied to know the role of CPA in cooperating with others for serving South Asia by providing integrated maritime logistics support efficiently and economically.

4. Limitations

The related experts who are in driving positions as port users, traders and port authority representatives, all replied that research is essential to develop the port sector of Bangladesh. But nobody is interested to provide answers officially. That resulted in a small sample size in qualitative data collection (21 out of 60 which is only 35%). In addition, it was not possible to quantify the amount of investment by CPA to other national ports such as Payra and Mongla also inland terminals PICT (Pangaon Inland Container Terminal) and Dhaka rail ICD.

5. Literature Review

To follow the research methodology, the port cooperation paper of UNCTAD [12] is reviewed to find out the gaps in port development. The basic approach of this research is to develop the port sector of Bangladesh by using the performance, productivity and strategic position of Chittagong port. The direct literature of Chittagong port is rare where related literature is attributed accordingly. Mention that port development is not increasing land and other facilities, it is crucial to attracting the port users by showing that port authority increased the land and others by creating synergies in developing connections in the port clusters [13]. The issue of competition and cooperation among the various players is always important in the cost-profit trade-off involving risk evaluations in port management. In some geographical contexts, the researcher found the tendency toward cooperation between ports is both organic and part of a deliberate strategy to promote competition within a shared hinterland [17]. The literature review mainly focused on the three basic indicators which are port performance, competitiveness and governance discussed one after another.

5.1 Port Performance

The requirements for seaport services are growing day by day to cope with the increased demand for cargo and information flow [14]. As container traffic keeps growing and physical expansion is constrained by the limited supply of available land around most ports, port facilities will need to become more productive if they are to remain competitive where assessing how ports perform is useful not only for transport planning but also for informing port management, policy, and regulation [15]. In addition, Cariou et al. [16] addressed the challenges in cargo handling operations particularly in a container that needs of going beyond ports within their seaport activities. Mention that the port reform initiative helped some countries with their significant improvements in port performance whereas others are re-thinking or yet not started the process because of its complexity and adjustment over time [17,18]. Port productivity and performance are related to the effectiveness of the supply chain as a whole where ports and users can take advantage of complementary strategies and capabilities to improve the port performance technically [19]. In the empirical analysis, Zhao et al. [3] provided their concept on the port characteristics where maritime connections, hinterland connectivity and port efficiency are the major variables in port networks. Talley [20] concluded that technically efficient optimum throughput, cost-efficient optimum throughput and effective optimum throughput are the economic objectives of a port that will satisfy all stakeholders of a specific port.

In the context of port performance, Dappe and Suarez-Aleman [15] identified three major viewpoints which are operational, economic, and financial. Here, the operational perspective refers to the quality of the outputs provided in port services and facilities efficiently and timely. After that, the economic angle takes into account factors such as the mix of inputs used, the technology used to transform inputs into outputs along with the port's productive scale. Twofold objectives of the port are strategic productivity and growth that are related to efficiency and expansion of the port performance respectively [10]. Lastly, the financial perspective addresses the mix of financial resources and profitability indicators. However, ports are complex places where performance is influenced by many factors including size, location, ownership, infrastructure, facilities, and others, but people or human resources are the most vital resource to get optimum performance [21]. In addition, smart ports always adopted smart people to show their efficiency in port operations and management. Throughput volumes are the main indicator in measuring port performance in the port industry, but it is not the regional economic impact of the port and its attractiveness to the port-related industries in the region [9]. A port may reduce time-related costs by reducing the congestion and turnaround time of the vessel that processes the quality of the port service as a part of port performance, in general [20].

5.2 Port Competitiveness

Port competitiveness has focused on the analysis of specific services rendered by ports or port activities where actors are involved often motivated by opposing interests and non-convergent objectives [22]. Historically, port authorities were created at the national or regional level for integrating the port activities and also for port development [17]. The port authority is a part of port community that is composed of a set of actors that are related to logistics lines and also lead and drive the port community [10]. Hales et al. [23] showed the significant effects of five variables of Volume Competitiveness (VC) and Investment Competitiveness (IC).

Identification of drivers of port competitiveness and identification of together with the measurement of the drivers in economies of scale in shipping especially being proactive in making hinterland strategies by port authorities, governance changes in framework and management level of port authority, degree of competition for attracting customers and investor, inter-firm networks in building relations between local and international stakeholders and in the aim featuring green and sustainable port planning efficiently [24]. The variables that are stated by Hales et al. [23] in Figure 1 and Parola et al. [24] in Figure 2 are common factors that need to consider by all for port competitiveness and taking the initiative to develop and compete in the business rivalry of the port sector in the South Asia or Bay of Bengal.

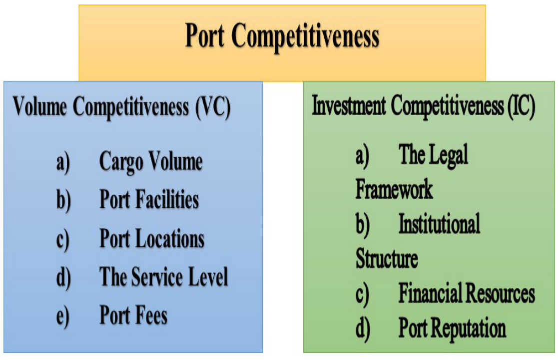

Figure 1. Port competitiveness [23].

5.3 Port Governance

The port policy generally and port governance more specifically reflected the changes in government and politics within a nation always [17]. Public port authority acts as both landlord and regulatory bodies where port operations are performed by private companies denoted as the best model of port governance [18]. Port governance always increased the port's effectiveness and competitiveness in the change of port management. The change in governance structures constitutes an important pillar in view of the achievement of sustainable development of ports including economic, social and environmental challenges. A port that was denoted as major engine for driving economics is a significant lever for governance to manage trade and catch economic benefits nicely [25]. With enormous containerization of maritime cargo, the container port industry is very competitive in serving the hinterland by filling all kinds of demands where South Asian countries' port tariffs are reasonable, but associated cost or indirect costs with the port tariffs are very high where inefficiencies play a more significant role in shippers' port choices [15]. Extension of ports often failed due to the lack of attention to the potential negative environmental impacts [8].

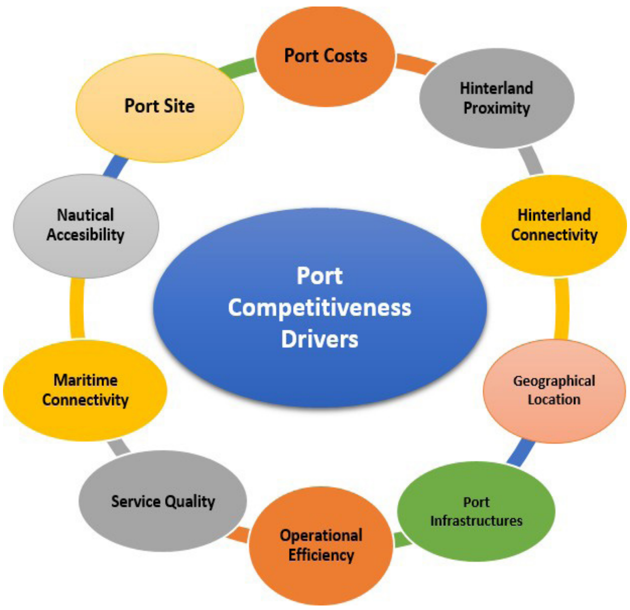

Figure 2. Drivers of port competitiveness [24].

The intermodal transport development has a great impact on further economic globalization that changed the overall transport system and supply chain where functional integration is impossible without intermodal transport chain [26]. Nowadays, ports are facilitating intermodal transportation directly to the shipper/consignee as a part of integrated maritime logistics support and increasing the hinterland. National and regional interests, as well as those of port cities, are often at odds with each other. Most importantly, the inland transport network is an obstacle by the government on the false plea of safety, security and religious politics [27,28]. Lastly, due to the ongoing commercialization of port authorities and the progressive pressure of stakeholders, port performance indicators are in new shape with the socioeconomic interest in a port [9]. Consequently, port authorities are in charge of hardware dimensions of port development for ensuring and enabling efficient management of supply chains through policy actions that should be aimed at improving infrastructure and inland connections by keeping the criteria of environmental, social and economic sustainability to promote the hinterland and ensure [22]. International organizations like the IMF (International Monetary Fund), and World Bank believe that South Asia presents a bright spot amid the gloomy global outlook [29]. In Bangladesh, Chittagong and Mongla ports are managed by port authorities where major approval authority is the Ministry of Shipping under the government where CPA exercises a high-level degree of operational and financial autonomy [15]. The South Asian port sector attracted significant interest from private investors in the late 2000s. Development of port facilities at Chittagong Port Bangladesh's largest port has been slow. Although occupancy at the CPA container berths is high and rising, there is a pressing need for more investment in a capacity where Mongla has had excess capacity for many years [15]. Intermodal freight transportation is lagging behind in Bangladesh and there is no established intermodal network except the Chittagong-Dhaka container transportation with the general rail network. Recently added the RICT (Riverine Inland Container Terminal) that named "Pangaon" in Dhaka but it also handling in Chittagong port yard. Ports are an integral part of the supply chain for managing and coordinating the materials and information flow [14]. Despite the predilection for promoting port privatization, full privatization has not been without its problems and critics [17]. Due to the complexity of seaports and the large number of firms in a port, port performance indicators are useful to measure whether the development of the port is satisfactory or not and learn how to improve the performance also communicates the performance of the port to a wide range of stakeholders [9]. To enhance the capacity of a port management, it is essential to strengthen the networks of the Hinterland exclusively. The development of the global supply chain bounded to change the traditional role of ports (Loading and discharging operations) and enhanced the capacity to a new role as efficient distribution of products across the supply chain and integrated logistics service providers as a part of the global distribution channel [19]. Port investors always look forward to tying with the port cities to get all kinds of logistics facilities and security for supporting the maritime trade because port-city relationship exhibits substantial significance in the development of port by attracting international investor and their hinterland while also sufficient spatial economic disassociation and environmental tension [3]. Talley [20] advised considering the operations, economic and port management objectives in port performance.

In summary, the above-mentioned literature demonstrated the port performance, competitiveness and governance are appreciated in that port development to build strong relationships among the stakeholders by port authorities. In addition, the intermodal network is very weak in Bangladesh and South Asia, for this reason, Bangladeshi ports are unable to expand their hinterland and go to the neighboring area's in the lack of regional cooperation and desire for transport integration among the South Asian countries apparently.

6. Qualitative Research Survey Findings

The five main basic research questions are guiding this paper as the theme of the qualitative research survey with the aim of open-ended questions. In order to explore per questionnaire, 21 interviews were conducted from June 2018 to August 2018. After field testing and setting the research questions, an invitation was sent to 60 persons who are experts in the shipping field, port management and port users. Here, questions are asked to the respondents with the aim of acquiring knowledge on port development in Bangladesh as below:

6.1 Role of CPA in Developing Other National Ports

Possibly, the existing development status of Bangladeshi ports where the role of CPA is appreciable because of their participation in establishing the third seaport Payra and full finance in constructing the inland riverine container terminal "Pangaon". However, the role of CPA in logistics and supply chain is very crucial in terms of efficiency, competitiveness and value-added productivity. The port has a congestion problem where vessel turnaround time is comparatively high. However, the technique of handling cargo and containers by expert persons of the port authority is appreciated by the port community of the world. There are lots of opportunities for CPAs to work in the port and maritime logistics parts especially in the development of Rail, Road, Inland waterways, Coastal, Airport and time-trend.

Mongla port is the underutilized port in Bangladesh where the government established a new seaport Payra to facilitate the demand for deep seaports as well as serve the neighbouring countries of South Asia especially Nepal, Bhutan and Seven sisters of India. It is argued that financial, technical assistance must be provided to other seaports for the development and as a part of corporate social responsibilities, in addition, to the exchange of human resources and deploying them in other ports for training and develop the employee of Mongla and Payra ports. All respondents advised them to CPA for taking leadership in developing the port sector and provide financial assistance to other ports from their profit and contingency fund also arrange finance from a financial institution or government to invest in the port infrastructure, purchasing equipment and other development works by which other ports can show the productivity and attract users.

In addition, CPA is technically sound in managing port operations, vessel management and port affairs where they can assist other ports by giving technical assistance for increasing efficiency. One respondent suggested that CPA must create the environment and situation by liaison with the government and private sector for developing other national ports for captivating the continuously growing volume of freight and container and need to think together.

6.2 Integration among the Seaports of Bangladesh

This is the time to integrate all seaports of Bangladesh and decrease the dependency on Chittagong Port where CPA has to play a vital role to develop all seaports. Respondents were tensed about the labour productivity, performance of equipment and wretched condition of roads and highways, poor railway connection, etc. They thought that CPA has to work on the quick development of all ports to cope with the containerization and mechanization of ports with the port hinterland freight distribution system and support the foreland by establishing a floating terminal in the Bay of Bengal. In addition, they appealed to the government to consider port planning and development as a priority activity to facilitate all trades in the country.

Moreover, integration is highly required to fulfill the standard demand of OBOR (One Belt and One Road) and competition may be raised among the seaports of Bangladesh, India and Myanmar enthusiastically, therefore, integration among the ports of Bangladesh is appreciated to help each other in the process of development. However, the need to comply with the basic goals of various forums like *BBIN* (*Bangladesh-Bhutan-India-Nepal forum for transport connectivity*), BCIM (Bangladesh-China-India-Myanmar forum for Regional Cooperation), BIMSTEC (The Bay of Bengal Initiative for Multi-Sectorial Technical and Economic Cooperation), *SAARC (South Asian Association for Regional Cooperation*) and *ASEAN (Association* of Southeast Asian Nations) etc. Lastly, all claimed to set the deep seaport in Chittagong and initiative must be taken by the management of CPA.

Overall, all respondents discussed that the integration of all seaports leading by Chittagong Port will make a chance to provide transit facilities to the neighbours by rail, road and river. In addition, CPA will finance the inland connectivity infrastructure cost where a good port transport network will be developed and respondents were optimistic about the process of port development. Mention that this transit issue is forecasted as derived demand of using Bangladeshi seaports, especially by India, Nepal and Bhutan [30,35] as per Figure 3.

Figure 3. Inland transport connectivity and the role of Chittagong Port as a development partner of other national port Mongla and Payra [30].

6.3 Challenges in Developing the Port Sector of Bangladesh by CPA

It is not easy to develop the port sector by CPA as Bangladesh is facing huge obstacles in developing the port sector. Latest experience in setting deep seaport in the Sonadia. Most of the respondents argued that CPA is facing huge challenges in developing the port sector of Bangladesh. Recent participation in building the inland container terminal "Pangaon" nearby the capital city Dhaka is appreciated by all, in addition, to direct involvement in establishing the 3rd seaport "Payra" in 2013. However, CPA is facing challenges in developing its own capacity and striving to increase the container jetty, terminal and handling equipment. Furthermore, the below challenges are discussed arguably.

Respondents found too many challenges in developing the port sector of Bangladesh and stated as below:

• Geopolitical and foreign policies are affecting to take strategic decisions in the port development of Bangladesh especially negative approaches of neighbouring countries by which deep seaport construction is delayed and not sure of its finance in the Bay of Bengal.

• Poor quality of roads and highways along with old models of trucks and trailers that consume passage time also environmental degradation by CO_2 emissions highly.

• Shortage of liaison among the port authority, City Corporation and city development authority to make common development of Chittagong port.

• An inefficient transit regime with a lag behind transport infrastructure and not having the future trade forecast for the region and country that is not facilitating or increasing the cargo and container handling capacity of Bangladeshi ports individually.

• Research on port development regarding Bangladesh and South Asia is fully absent and undermined for a long time and not considered by all where ADB is trying to forecast some data and related research is conducted by the World Bank on a minimum scale.

• To create synergies in the port sector by making common standards for all ports and rendering guaranteed reliability to port users.

• There is no benchmarking statistical data for the port authority to take a decision on how much development is required in terms of infrastructure and others and the port has to follow the full government process of procurement that time bounded.

• Continuous pressure on CPA for managing all cargo and containers where other ports are under-utilized. In this connection, cooperation from the government, port users and others is limited to divert the vessel or container in an alternative way.

• The political will of the government in the port development and consideration of development projects and finance over there as the government has to perform in all cases.

• For environmental sustainability, priority may be given to the intermodal instead of multimodal that pollutes the environment and need to use various modes of transport at different points or nodes. In addition, internalization is a great challenge to face congestion, local pollution, accidents, GHG & CO_2 emission, energy efficiency, etc.

• The desire of neighbours and world port investors for capital investment and making a regional port in Bangladesh where Chittagong is viable in all aspects.

• Development of a rail transport network with spatial transportation and introduction of a Double Decker container transport line between the major cities of the country.

• Full privatization of port sector or develop the port under the banner of PPP (Public Private Partnerships) to reduce the pressure of capital investment by port authority.

The most important statement received was "every challenge is achievable subject to the dedication of all port authorities and positive approach of the government by putting the port sector in their political circle". Forecasting the increase in port throughput, due to infrastructural enhancement, is a major challenge for many different reasons.

6.4 Sustainability of Port Sectors in Bangladesh

The experience of CPA will help to take national approaches to sustainability in the volatile port sector and the role of government is highly appreciated. "Port Cooperation" is the main theme of port sustainability that may exceed from the national boundary to abroad by making liaison with neighbours ports or international forums of the port authority or associations. The turnaround time of an incoming vessel in Chittagong port is very high in South Asia but the average performance in managing container vessels is good. But there are some records of collapsing the total supply chain of the port that is harming the brand name of Chittagong Port as well as the country. Due to the breakdown in managing container flow, ocean freight is increased by the international carrier unjustifiably. On the other hand, CPAs are used to manage such a crisis from their vast experience in the port sector. Critically, the bad performance brought negative opinions in the mind of respondents where they argued for good port management by experienced people in Chittagong port and suggested making contingency or backup plans for avoiding such situations that bound to pay extra for the port users unexpectedly.

Respondents described the worst situation of Mangle port and its authority (MPA). They found an idle and unskilled person who is managing the port only by name without adding any value-added service to the port users. Several times, the government had taken necessary initiatives to bring efficiency and attract the business community to use the port at a minimal tariff, but due to poor category service, interest in Mongla port is uncertain. Most of the respondents were advised to take over the MPA by CPA and manage accordingly. To sustain the current trends of port activities, respondents suggested taking a long-term development plan and may lease the Mongla port to the international terminal operator who will handle the operations as well as manage the customer by fixing the hinterland. Environmental sustainability is a growing concern of the port industry and needs to promote intermodal transportation, which is environmentally friendly and make long-term sustainable development of the port in developing energy and operational efficiency plan at the port yard and inland transportation. All appreciated the steps by CPA for taking Carbon Tax from vessels under the port-protected areas of CPA.

6.5 Inland Transport Networks Development

Two important issues are key factors in port development, one is inland transport network development and another one is specific IFT (Intermodal Freight Transportation) system development for facilitating the inbound and outbound freight by applying just in time approach. Greatly, 21 respondents argued for road modes for developing inland transport networks in Bangladesh urgently where CPA may play a vital role in assisting the government and other port authorities by providing financial assistance or arranging finance for inland transport network development by using the surface or spatial transportation rather than choosing rail and waterways modes exceptionally as the road is speedy transport mode in Bangladesh till date.

All respondents favored the urgent development of roads and highways because congestion and passage time are very high which resulted in high freight for sending cargo to the port and vice versa. In addition, the intermodal freight transportation system will not be implemented without the good condition of roads and highways. After that freight rail network development is a priority area where CPA is able to invest in starting the Double Decker container line from Chittagong port to Dhaka and inspire rail authority in constructing a dedicated rail track for freight transportation as rail is cheap and safe transportation system and suitable for intermodal transportation. Lastly, they argued for inland waterway transportation and are happy to know that the container is transported by waterways from Chittagong to nearby Dhaka.

For better utilization of existing trucks and trailers, it is of utmost requirement to renovate all roads and highways with bridges and culverts. Emphasize given on the access roads to ports and major cities and industrial areas. Most of the respondents deliberated their opinion on transit facilities to the government and stated that the present condition of road and highways are not suitable to provide such facilities to anyone. Even so, it is hard to mitigate the domestic's demand for port transportation facilities to cover all import-export trade timely. One respondent stated that only for bad road communication, Mongla port is underutilized. Therefore, need to invest in the infrastructural development of roads and highways where CPA may invest to create better facilities to/from the access port easily.

CPA has its own ICD (Inland Container Depot) in Dhaka and the container is in operation from Chittagong port to Dhaka and respondents are worried about the time that is taken by the rail hugely and not appropriate in container transportation. For any container transportation, it is taking 5 to 6 days whereas road haulage time is a maximum of 2 days. Overall, current rail transportation is not feasible for all and needs to improve the freight rail networks. Furthermore, we have the best connection to inland waterways. The recent development of RICT nearby Dhaka and the opening of the door to private investors for constructing private RICT may improve inland waterway transportation. Some respondents argued for common transport networks in three seaports to exchange the equipment and preserve special funds for emergency response in a breakdown in any ports and quick renovation of inland transport networks. In addition, for smooth operations of break-bulk cargo in the Bay of Bengal, a quality coaster or inland vessel is required to decrease the turnaround time and it is essential to establish a floating terminal for avoiding multiple handling of cargo & containers in the port jetty. It will attract coastal shipping among Asian countries and direct entry to the inland terminal. Some of the respondents attended in the open-ended questions where they suggested CPA take full responsibility to build an integrated intermodal freight transportation network of road, rail and inland waterways for domestic container transportation and establish a dry port nearby cross-border to provide maritime logistics support to the neighbours for doing "Transport Business" and arrange same for other national ports.

7. Compare and Contrast

With the aim of developing seaports, many governments created port authorities especially to progress the port development commercially [13]. Based on the literature and qualitative research survey, the below points are considered to bring the standard of maritime logistics of Bangladeshi seaports with the aim of serving nationally, regionally and internationally: The shipping industry is showing the potential to improve the energy efficiency that started from ocean passage to shipyard (terminal, jetty and other places) and it's a part of port performance in the present world [31]. Another factor that is influencing the port authorities to inspire the shipping companies to use natural gas (LPG-Liquefied Petroleum Gas, LNG- Liquefied Natural Gas and others) instead of fossil fuel. To cope with the challenges and opportunities of the 21st century Maritime Silk Road for better connectivity and economic cooperation, it is essential to develop the country itself to stay in the Bay of Bengal meaningfully and had the opportunity to serve the landlocked region, India's northeast, China's southern, Nepal and Bhutan that would be the value added to the regional development and economic growth [32].

In Figure 4, Bangladeshi seaports are well connected with the regional hub port Colombo, Sri Lanka, Klang and Tanjung Pelepas of Malaysia and Singapore. This research found the opportunity to stay within the region which means tagging with Chennai and Visakhapatnam of India, in addition to Colombo, Sri Lanka. Strategically, it will increase the regional bonding in South Asia and open the opportunity for Indian ports for using Bangladeshi seaports as a maritime load center for Seven Sisters of India, Nepal and Bhutan. As India is a good development partner of Bangladesh and is interested to use Chittagong and Mongla Port for their basically landlocked parts, it will be a great opportunity for Bangladeshi ports for developing port facilities through the leadership of Chittagong Port actively.

Figure 4. Foreland connectivity of Bangladeshi seaports developed by the author. Map was taken from Google [33].

Alam [28] stated that Bangladeshi ports are able to serve as the gateway to reach the landlock Nepal & Bhutan, India's seven sisters for facilitating global trade. Moreover, he added that subject to port development, it is possible to connect ports with Southern China and it will be the great one in between the overland surface road and maritime Silk Road. Environmental sustainability in any seaports that need innovation where research is required to make it successful. Safety and security are great concerns for hinterland operations by ports where the port has to clear all the obstacles for attracting the port users or traderS within the established hinterland [34]. However, to overcome the challenges and problem areas will need the political will to facilitate the changes because the government is continuing to fight financial fires and ports are perhaps not a key priority in many cases [17]. Overall, structural, operational and organizational changes are required for strengthening the capacity of CPA to build the port sector from the viewpoint of port performance, competitiveness and governance.

Finally, Chittagong port has the first mover key advantages in the Bay of Bengal or South Asia to provide maritime logistics support and offer free access to all where port development is essential. Developed ports added some new indicators like emissions of greenhouse gases, investment flow and economic impact of a port but remember that depending on the port structure, different performance indicators are relevant for different ports [9]. The concept of integration in the port sector is highly concerned with the intermodal activities that focused on the conditions of efficiency and effectiveness of intermodal container transportation, and organizational integration that is undertaken by foreland & hinterland connections [22]. Lastly, activities, resources and inter-organizational relationships between the players in the network are critical and essential to the port's value created by port development. A successful growth strategy for South Asia would need to rely on a balanced, multifaceted approach in a dynamic global environment [29]. This is due to negative outlook for ports and existing operating environment is really competitive, risky and mired in slower growth. This is true that port infrastructure is still relatively backward and not in a standing position with the internationally developed port standard comparatively. Greater uncertainty in the operating environment, governing policy, and sufficient infrastructure development to make a model port in South Asia, still Chittagong port is lagging behind accordingly In this connection, it is a good way to develop other national ports and divert the cargo and container to reduce the pressure towards CPA. Overall, port development is essential and it may be done by CPA or the Bangladesh government urgently. Here, trade forecast, regional development and recent institutional cooperation are the national and international pressure to develop Bangladeshi seaports inevitable and urgent.

8. Regional Common Platform for Transport Connectivity

South Asia is an important place for moving business trends to Asia where the location of Bangladeshi seaports is important strategically and a key factor for all to do foreign business as well as export and import trade profitably. Port infrastructure development is highly important to regional economic development [13]. For a common platform in providing seaport access to all in a specific region, it is important to cooperate with each other irrespective of profit or port rivalry where it may be treated as social responsibility. Goals are too general to provide sufficient directions for the authority and reform as and where required and increase the ability to safeguard the public interests of the country and region proudly. The absence of transit agreements for a long time among South Asian countries fractured the regional integration process [28]. In addition, underpinning all trends of greater devolution, privatization and communication and approaches the desire to govern ports in a way that makes them more profitable and efficient, and, increasingly, a way that makes them more sustainable and greener [17].

Bhatta [36] examined that regional economic integration depends on the commonality of the political purposes of the member countries where India has to favor and sacrifice to all for emerging as a regional entity in the international political system. However, a recent initiative of India and Bangladesh in developing transport connections in the region is moving ahead toward increased regional participation in trade and commerce [28]. In relation to improving the global transport system, the availability of transport operations contributes to the value creation for accomplishing the qualitative attributes of demand such as reliability, punctuality, frequency, availability of infrastructure and security [14]. To assess the disruption risk of Asian ports, Lam and Su [37] identified that climate change, oil spills, security and social and political instability are increasing the concern to all. As trade volumes are growing significantly, port disruptions are comprehensive studies for putting operational performance. A reliable freight transport system is essential for the modern world economy where marginal supply chains are involved with seaport activities greatly [37].

Overall, the regional common platform for transport connectivity highly depends on two factors: The openness of India to open the so-called "Chicken necks" land connection among India, Nepal, Bhutan and Bangladesh that will allow getting free access by all including China and Myanmar: another one is the free access opportunity in Bangladeshi seaports subject to the development of inland transport networks by Bangladesh.

9. Conclusions

Chittagong port is the principal seaport of Bangladesh managed by the CPA and is able to serve all modern seaport facilities to the port users for driving above 90% import-export trade of Bangladesh [38]. Port authority in leading leadership roles sets the larger role for terminal operators who bear the market's considerable risk and face the demands of an increasingly stringent environment regime [5]. Bangladesh acutely needs the deep seaport in the Bay of Bengal to increase the supply side against the increased demand for port facilities, in addition, to supporting the neighbours or region for doing port transport business as a part of economic sustainability [32,35]. Historically, the port is the entry point of international trade for a country that helps to attract the international trader to do business and it's a key logistics performance indicator. A recent development in port sector is containerization and mechanization, and the port has to set as per new dimensions that are required by international shipping company and terminal operators. In this context, De Langen and van der Lugt [13] argued from the operational perspective of public sector port authority for promoting general interests the port operations handled by third parties are a part of port development. Nowadays, port authority is an increasingly commercial role to bring the developer or work as a port Development Company due to the containerization and mechanization of port activities also developing inland connections with the urban cities and major industrial areas.

Remarkably, the continuous changes in the international maritime transportation and further movement of cargo and container towards the hinterland, structured the total transportation solutions to the port users, traders and stakeholders accordingly. Due to poor connection between the Bangladeshi seaports and hinterland as well as inadequate standard port facilities of Mongla port, Chittagong port has to manage the excess pressure of freight and face challenges in providing maritime logistics support to mitigate the demand of domestic port facilities where opportunity remains to serve South Asia by using the geographical advantages or positional standing in the Bay of Bengal greatly. This paper aimed to explore how CPA assists other national ports and port infrastructure that will be developed with the port efficiency and productivity and all ports will serve the nation equally against the domestic demand of maritime logistics or port services. In line with such motivation, Mongla and Payra will develop accordingly to supply port services to the neighbours India, Nepal and Bhutan as well as serving the South-West part of China with the aim of increasing regional connectivity and promoting international trade in those basically landlocked areas and countries of Asia. Overall, future directions will help to CPA for playing a vital role in port development and related infrastructure development in Bangladesh for doing "transport business" in South Asia.

10. Future Directions

On the basis of the literature review, qualitative research survey and innovations for the seaport, research attributed the below future directions for port sectors of Bangladesh as well as for CPA that will help them in the process of port development in Bangladesh:

1) Bangladesh is the only country in the Indian subcontinent in which the private sector does not play a meaningful role in the container port sector [15]. Therefore, port privatization scope needs to inspire or utilize and make joint ventures with local and international investors in the port sector as a cheap way to develop the port economically.

2) PPPs model has advantages in funding where ports are able to build and updates the assets such as handling equipment, container storage facilities, channel dredging and others including infrastructural development [23]. To attract international investors in the port sector, it is good to appoint international terminal operators. Nowadays, terminal operators are managing not only the terminal but also managing the customers of the hinterland and increasing the hinterland by offering various port services at an affordable price.

3) Port users are always thinking about the port facilities, but it is also a factor in selecting port that has good inland transport connections with the shipper/consignee premises. Thus, emphasis should be given to the inland transport network development.

4) Most of the containerized cargo is managed at the dry port and must have a rail network to connect between the port and dry port, in addition to a road connection. Bangladesh has to build dry ports with smooth inland connections with ports in major cities for domestic cargo and in cross-border areas to serve the neighbours.

5) Having the opportunities to provide maritime logistics support, Bangladesh has to open the door of ports and promote regional connectivity in the transport sector.

6) Government has to follow up the Logistics Performance Indicator (LPI) of the World Bank and must take necessary reform initiatives to increase the value of LPI for attracting the world trader to do business with Bangladesh and use the Bangladeshi seaports in the competitive port tariff.

7) Geopolitics is a problem for investment in the port sector where India and China is a key factors to build a deep seaport in the Bay of Bengal [32]. Government has to take a deep seaport initiative in Chittagong and share with the development partner countries for investing in the deep seaport projects.

8) With much talk, the floating crane is an innovation for ports that increased productivity and promote the modal shift for handling a large volume of containers [5]. CPA has to take the initiative to set up a floating container terminal for handling feeder vessels towards Mongla, Payra

and RICT Pangaon to save time and decrease the number of handling at the port area.

9) Maritime governance is playing a key role in developing the prestigious standing in the world [39]. To integrate all seaports of Bangladesh, it is essential to create a maritime commission for monitoring the port productivity, governance and facilities.

10) Research is a developmental feature to focus on the gaps and necessary guidelines and directions to take initiative for future development. Research on port development is essential as this chapter is far lagging behind in Bangladesh including South Asia.

Conflict of Interest

The opinions are solely from the researcher and there is no conflict of interest with the employer *Saif Powertec Limited*. Mention that *Saif Powertec Limited* is not involved in any part of this research and is not responsible for any comments from anywhere.

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ARTICLE

Vibration Isolation Characteristics of Impedance-balanced Ship Equipment Foundation under Unbalanced Excitation

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ABSTRACT

A new type of impedance-balanced ship equipment foundation structure based on the principle of impedance balancing using a “discontinuous panel-vibration isolation liquid layer-foundation structure” is proposed to solve the problem of poor low-frequency vibration isolation of the foundation under unbalanced excitation of shipboard equipment. Based on the finite element method, the influence of characteristic parameters of the foundation panel structure on its vibration reduction characteristics under unbalanced excitation is explored. The results show that the vibration isolation level of the impedance-balanced foundation is 10 dB higher than the traditional foundation in the low-frequency band of 10-500 Hz when subjected to combined excitation of concentrated force and moment. Increasing the thickness of the impedance-balanced foundation panel can enhance the isolation effect. Increasing the number of sub-panels can effectively reduce the vibration response of the foundation panel and enhance the isolation performance of the foundation. The connection stiffness between sub-panels has a small effect on the isolation performance of the foundation.

1. Introduction

As the main structure connecting the equipment to the ship structure, the equipment foundation acts as a main medium for the transmission of vibration energy from the equipment to the outside of the ship. The impedance characteristic of the foundation is a critical parameter that characterizes the ability of the foundation structure to resist mechanical vibration. It is also the main index to reflect the vibration isolation performance of the equipment foundation [1,2]. Thus, the analysis of foundation impedance is important for the vibration reduction and isolation design of the foundation structure [3,4].

To enhance the vibration isolation performance of equipment foundations, Peng [5] proposed an impedance matching design method for ship foundations. This approach modifies the structural characteristic parameters and shapes of the foundation to achieve mutual matching between its impedance and that of the internal excitation

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source, thereby achieving low radiation noise levels for ships. Li [6] compared the vibration acceleration and underwater radiation noise of the foundation structure before and after the installation of damping materials, which provided support for the low-noise optimization design of the surface ship structure. Wang et al. [7] found through research that the application of damping materials can reduce the value of equipment foundation vibration amplitude in the intermediate frequency range above 60 Hz. Yang et al. [8,9] proposed a unified impedance model for ship vibration reduction that comprehensively optimized the structural dynamic layout of stiffness, damping mass and damping material to enhance the vibration reduction capability of the foundation structure. Ling and Wu [10] used the finite element method to study the suppression effect of multi-stage isolation mass on structural sound propagation. Liu et al. [11] further revealed the suppression mechanism of vibration damping mass on structural sound transmission through case analysis and experimental verification. Yuan et al. [12] discussed the two indirect force estimation approaches, and experiments showed that indirect approaches could be good choices for determining the output forces of machinery in ships. Chen et al. [13] established an isolation vibration system with distributed dynamic absorbers and found that it could increase the frequency range of the absorbers. Ye et al. [14] combined a mathematical model of particle damping, developed a design method of particle damping optimization, solved the problem of high-frequency vibration in the power device, proposed to combine it with active control technology, and verified that it can achieve low-medium-high broadband vibration control of ship equipment. Based on scaled model experiments, Wu et al. [15] proposed a hysteresis nonlinear foundation structure with MRD and verified its effectiveness in low-frequency line spectrum vibration. Gong et al. [16] discussed the effect of damping mass on the propagation of vibration waves in pipelines based on the impedance mismatch principle and numerical analysis methods, and the results showed that damping mass has a beneficial damping effect in the medium to high frequency range. To achieve the purpose of impedance mismatch, Qi et al. [17] used a modern type of vertically symmetric foundation with low stiffness isolators and high input impedance to control the coupled vibration and noise radiation of the propeller shaft system. Wang [18] proposed the combination of active or semi-active control with dynamic absorbers to reduce the vibration transmitted to the deck and hull from power equipment and piping systems. Chen et al. [19] derived the expression of pressure-resistant strength of airbag isolators from the thin shell non-distance theory and verified the reliability of airbag isolators. Du and Li [20] investigated the nonlinear vibration mechanism of the ship rotating machinery with an airbag isolator under heaving motion. Bu et al. [21] proposed a multi-objective collaborative attitude control method for double-layer airbag isolator devices under flexible support conditions. To effectively reduce the vertical and horizontal stiffness of the airbag isolator, Yin et al. [22] adopted a composite airbag structure with serial hard-elastic layers. Li et al. [23] designed a highly adjustable magnetorheological elastomer-based isolator for real-time adaptive control, which can change the lateral stiffness of the isolator under moderate magnetic field levels. For complex mechanical systems, Wu et al. [24] analyzed the quantitative relationship between the impedance of the two transmission channel systems and the isolation effect of the mechanical system and the transmission loss of the pipeline system based on the hammer test method. The experimental results show that the impedance can be increased and the isolation effect can be improved by strengthening the foundation reinforcement or changing the elastic element properties/layout of the pipeline system. Ye [25] proposed a method to improve the impedance of the foundation by optimizing the structural variables of the foundation without altering the structural shape of the foundation and verifying its effectiveness. Dario et al. [26] developed an isolation system to optimize the tuned mass damper inertial device, which allows the inertial instrument and damper to be installed in series, resulting in a lower mass and more effective alternative than conventional tuned mass dampers. Maciejewski et al. [27] conducted numerical simulation and optimization design of a vibration isolation system. They established a mathematical model for vibration reduction and obtained an optimal method for high-efficiency vibration isolation by simulating the dynamic behavior of the system under diverse working conditions.

In light of the research summarized in this review, it is apparent that improving the mechanical impedance matching or impedance mismatch by increasing the damping mass, changing the shape or material properties of the foundation structure, etc. [28], has improved the vibration reduction and isolation performance of the system. It may be necessary to increase foundation mass or decrease foundation stiffness in order to further extend the isolation frequency range of the foundation using the method to lower frequencies, but doing so could result in issues like excess foundation mass or inadequate stiffness, which are detrimental to the lightweight design of ship structures and structural safety. Therefore, this paper proposes a foundation impedance-balanced method, which uses a vibration isolation liquid layer instead of the traditional foundation support structure in the design of the foundation structure to transform the excitation force point and line transmission into surface transmission. To improve the vibration isolation performance of the foundation, the impedance of the foundation is balanced and distributed by interrupting the continuous propagation of vibration waves through the discontinuous panel structure. The vibrational isolation effect of the proposed method is calculated using the finite element method, and the effect of the device foundation panel structural parameters on the vibrational properties is investigated.

2. Principles and Characterization Methods of Impedance Balancing

2.1 Impedance-balanced Principle

Assuming that the total force F and total impedance Z transmitted to the foundation structure by the same equipment are constant, the equipment is connected to the foundation structure through machine feet. The equipment excitation is transmitted only through the foot of the machine to the foundation structure. If the number of machine feet is n, the force transmitted to the foundation through the k-th machine foot is F_k, and the input impedance at the k-th machine foot is Z_k, so we have:

$$F=\sum_{k=1}^{n}F_k=\sum_{k=1}^{n}x_kF,\sum_{k=1}^{n}x_k=1 \tag{1}$$

$$Z=\sum_{k=1}^{n}Z_k=\sum_{k=1}^{n}y_kZ,\sum_{k=1}^{n}y_k=1 \tag{2}$$

where $x_k=\dfrac{F_k}{F}, y_k=\dfrac{Z_k}{Z}$, the total power flowing into the foundation is P.

$$P=\sum_{k=1}^{n}P_k=\sum_{k=1}^{n}\frac{F_k^{\ 2}}{Z_k} \tag{3}$$

From Equations (1)-(3), it can be concluded that:

$$P=\left(\sum_{k=1}^{n}\frac{x_k^{\ 2}}{y_k}\right)\frac{F^2}{Z} \tag{4}$$

When $x_k=y_k$, the system can obtain the minimum input power, that is, when the force/impedance distribution of the foundation is balanced, the energy transmitted from the equipment to the foundation is the lowest. Figure 1 compares the vibration response of the foundation structure under different loading modes. It can be seen that when the excitation force is the same, the vibrational response of the base structure is weaker when the force is uniformly distributed over the surface compared to the case of concentrated point force loading. Therefore, if the unbalanced excitation force of the equipment can be transformed into a distributed force, the transmission of vibration energy can be effectively reduced and the vibration isolation level of the foundation can be improved.

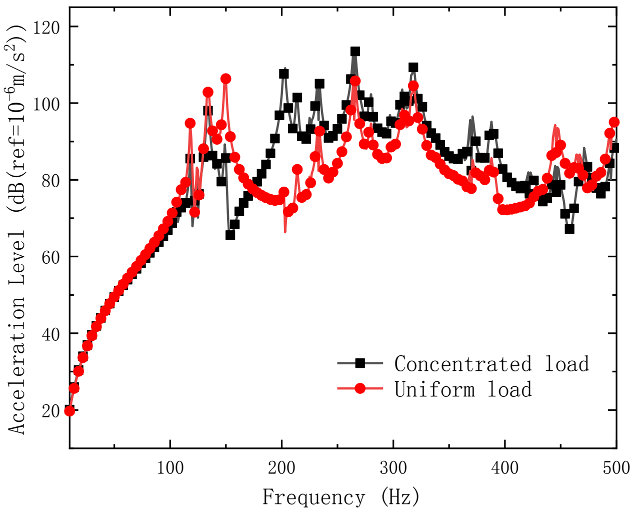


Figure 1. Comparison of average vibration acceleration levels of structures under different loading forms.

2.2 Impedance-balanced Characterization Method

This paper proposes the concept of impedance-balanced design for the foundation, which reflects the level of impedance balancing of the foundation under the current structure form through the difference of input impedance curves at several points in a certain frequency range. The specific definition is as follows.

Assuming that n loading points are uniformly selected on the surface of the foundation structure, each loading point has an input impedance $Z_0^i(f)$ at frequency f, and the standard deviation S_i of the n loading points on the foundation at frequency i is expressed as:

$$S_i=\sqrt{\frac{\sum_{i=1}^{n}(Z_0^i-\overline{Z_0^i})^2}{n}} \tag{5}$$

$\overline{Z_0^i}$ represents the average input impedance of each loading point at frequency i.

In order to eliminate the effect of high or low levels of data values on the dispersion of the sample values, the dispersion coefficient is calculated, which is defined as follows:

$$V_i=\frac{S_i}{\overline{Z_0^i}} \tag{6}$$

The ratio of the standard deviation to the mean of the data. Therefore, within the [a, b] frequency band, impedance standard deviation curve $R(S_i)$ and discrete coefficient curve $D(V_i)$, average the curve values at each frequency point, get foundation impedance discretization coefficient *ZDC*, defined as:

$$ZDC = \frac{\sum_{i=1}^{m} V_i}{m} \tag{7}$$

where *m* is the number of analysis frequencies in the [a, b] frequency band.

Similarly, take the reciprocal of the foundation impedance discretization coefficient to obtain the foundation impedance-balanced coefficient ZSC, which represents the degree of equipment foundation impedance balancing, defined as:

$$ZSC = \frac{1}{ZDC} = \frac{m}{\sum_{i=1}^{m} V_i} \tag{8}$$

3. Impedance-balanced Ship Equipment Foundation Model and Vibration Reduction Effect

3.1 Impedance-balanced Ship Equipment Foundation Model

This article proposes a new type of ship equipment foundation structure with impedance-balanced, as shown in Figure 2. Replace the complete continuous panel with a discontinuous foundation panel, and replace the traditional support structure with a vibration isolation liquid layer, so that the surface waves transmitted to the structure surface undergo waveform conversion at the fluid solid interface, diminishing in the form of liquid surface waves, so as to balance the distribution of input impedance at various locations of the foundation panel. Keeping the impedance dispersion coefficient curve of the foundation at a low level effectively reduces the vibrational response under the excitation force of the device.

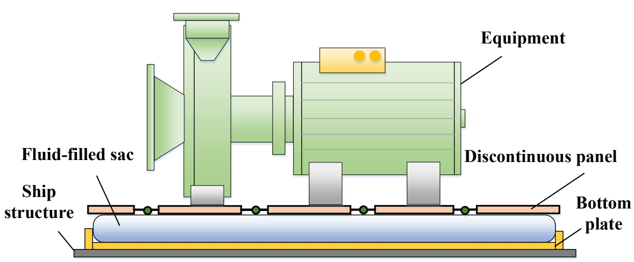


Figure 2. Schematic diagram of impedance-balanced foundation structure.

3.2 FEM Model of Impedance-balanced Ship Equipment Foundation

For complex structures such as the ship foundation, the finite element method is commonly used for numerical analysis. In order to improve the efficiency of simulation calculations, the paper proposes to use the structure-acoustic coupling finite element method for analysis. The liquid is assumed to be ideal fluid and the influence of the fluid-filled sac on the isolation characteristics of the foundation is ignored. The sonic wave is a small amplitude sonic wave and there is no energy loss during the propagation process. The structure-acoustic coupling dynamic equation is expressed as follows:

$$\begin{bmatrix} M & 0 \\ -\rho_a \bar{Q}^T & M_a \end{bmatrix} \begin{bmatrix} \ddot{X} \\ \ddot{P} \end{bmatrix} + \begin{bmatrix} C & 0 \\ 0 & C_a \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{P} \end{bmatrix} + \begin{bmatrix} K & \bar{Q} \\ 0 & K_a \end{bmatrix} \begin{bmatrix} X \\ p \end{bmatrix} = \begin{bmatrix} F \\ F_a \end{bmatrix} \tag{9}$$

M_a, C_a and K_a represent the mass matrix, damping matrix, and stiffness matrix of the fluid, respectively. p is the acoustic pressure vector, and K_a is the load vector of the acoustic field excitation. $\bar{Q}$ is the structure-acoustic coupling matrix, and ρ is the density of the fluid.

Equation (9) can be rewritten as follows utilising the modal superposition principle and the Helmholtz equation:

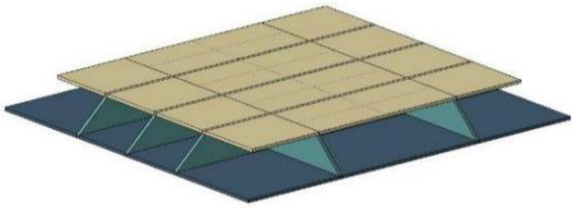
$$\begin{bmatrix} K + j\omega C - \omega^2 M & \bar{Q} \\ \rho_a \omega^2 \bar{Q}^T & K_a + j\omega C_a - \omega^2 M_a \end{bmatrix} \begin{bmatrix} X \\ p \end{bmatrix} = \begin{bmatrix} F(\omega) \\ F_a(\omega) \end{bmatrix} \tag{10}$$

where ω is the circular frequency, and $j = 1$, $F(\omega)$ represents the modal load.

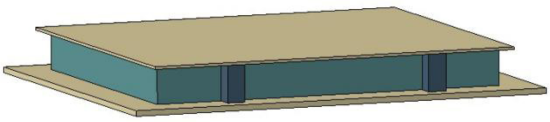
Equation (10) is the solution equation for structural vibration and radiated acoustic field based on structure-acoustic coupling theory. By solving the above equation, the structural vibration and radiated noise under a given excitation load can be calculated.

Establish finite element models for traditional foundation and impedance-balanced foundation structures respectively. The computational model is shown in Figure 3, where the bottom boundary condition of the foundation is fixed on all four sides. The load is applied to the foundation panel in the form of a unite excitation force. Spring elements are used to connect each adjacent foundation panel. After the convergence calculation, the finite element mesh size of the structure was set as 0.005 m while the acoustic mesh size was 0.01 m. The total number of finite element meshes is about 280,000.

The main structural parameters and material properties of traditional and impedance-balanced foundation are shown in Table 1. The main material parameters are shown in Table 2.



(a) Traditional foundation structure model



(b) Impedance-balanced foundation structure model

Figure 3. Schematic diagram of foundation structure.

Table 1. Main structural parameters of traditional and impedance-balanced foundation.

Panel size	2.0 m × 1.6 m	**Panel thickness**	0.02 m
Foundation plate thickness	0.03 m	**Web plate thickness**	0.01 m
Total height of foundation	0.2 m	**Liquid layer thickness**	0.2 m
Foundation material	Q235 Steel	**Liquid layer material**	Water

Table 2. Main material parameters.

Material	Steel	**Material**	Water
Density	7850 kg/m^3	**Density**	1000 kg/m^3
Elastic module	2.1×10^{11} Pa	**Bulk volume**	2.2×10^9 Pa
Poisson ratio	0.3		

3.3 Impedance-balanced Foundation Isolation Effect

As shown in Figure 4, to verify the isolation effect of the impedance-balanced foundation, the concentrated force of 1 N and moment load of 1 N·m were applied at the midpoint and both sides of the panels of impedance-balanced foundation and traditional foundation respectively. The calculation and analysis frequency band was 10-500 Hz. Set evenly distributed assessment points on the surface of the panel and bottom plate on the foundation, and use the average vibration acceleration level of the assessment points as the evaluation standard. The calculation results are shown in Figures 5-6.

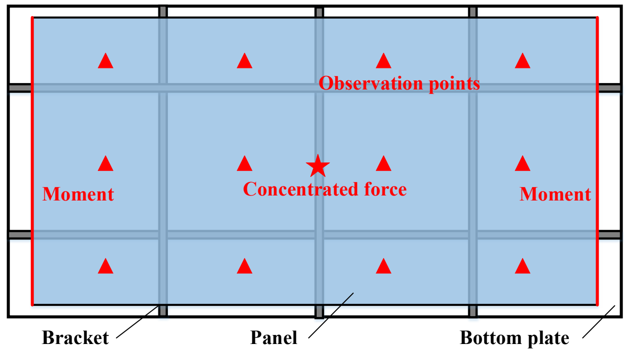


Figure 4. Schematic diagrams of measurement point layout and the loading situation.

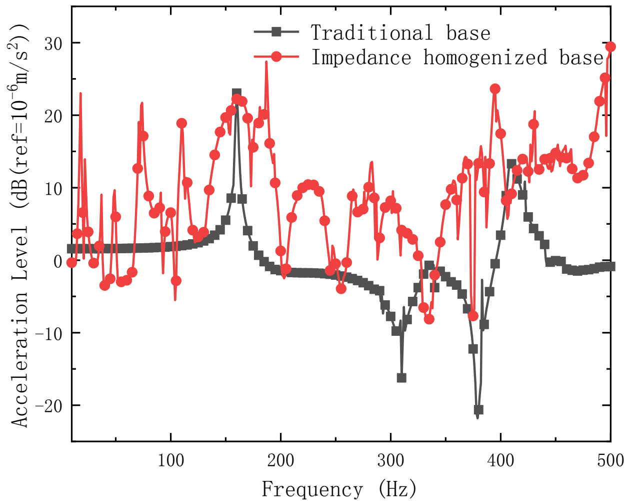


Figure 5. Comparison of average vibration level difference between two types of foundations subjected to concentrated force.

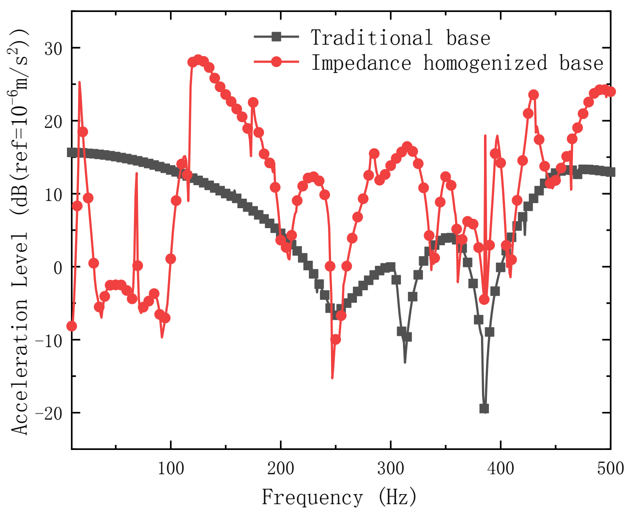


Figure 6. Comparison of average vibration level difference between two types of foundations subjected to the combined action of concentrated force and moment.

Figures 5-6 show that the impedance-balanced foundation performs better than the traditional foundation in the frequency range of 0-500 Hz when the foundation structure is subjected to a concentrated force, with an average isolation level of 10 dB higher than that of the traditional foundation. However, the isolation level of the impedance-balanced foundation in the frequency range of 0-100 Hz is lower than that of the conventional foundation when the focused force and moment load are coupled to the foundation. The impedance-balanced foundation's isolation level, which is more than 12 dB higher than that of the conventional foundation in the frequency range of 100-500 Hz, can reach up to 30 dB at the 125 Hz frequency point. Therefore, it can be seen that the impedance-balanced foundation has better isolation performance in a wide frequency range.

4. Analysis of the Impedance-balanced Foundation Isolation Characteristics

4.1 The Influence of the Structural Form of the Foundation Panel

The Influence of Panel Thickness on the Isolation Characteristics of the Impedance-balanced Foundation

Based on the above structural model, analyze and calculate the impact of changes in the thickness of the foundation panel on the vibration isolation characteristics of the foundation structure. To improve computational efficiency, the above model is further simplified into a shell structure model. The thickness of the foundation panel is 10 mm, 15 mm, and 20 mm, respectively. The calculation results of the average vibration acceleration level of the lower surface of the foundation are shown in Figure 7, and the difference in the foundation vibration level is shown in Figure 8.

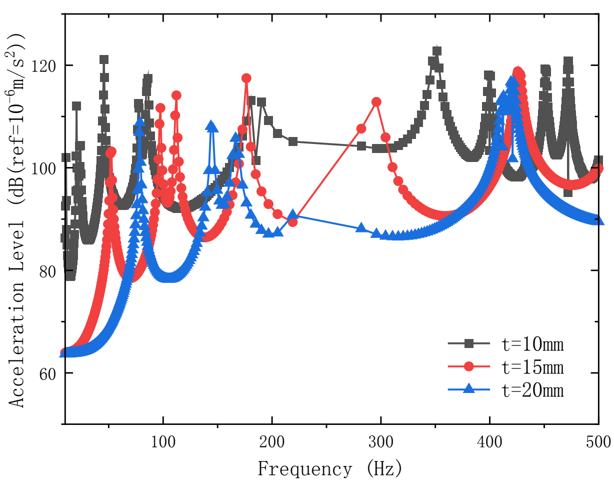


Figure 7. Average vibration acceleration level curve of assessment points with different thicknesses of foundation panels.

From Figures 7-8, it can be seen that as the thickness of the foundation panel increases, the average level of the assessment points of the hull structure under the foundation decreases overall. When the thickness is greater than 15 mm, further increasing the thickness does not reduce the system's vibration level. As the frequency gradually increases, the peak acceleration response shifts to the high frequency. This is because the increase in thickness increases the stiffness of the foundation system. By comparing the results in Figure 8, it is found that, although the increase in thickness makes the foundation exhibits a stronger vibration isolation effect at most frequency points, not all frequency point positions within the analysis frequency band have increased vibration level difference, and even negative vibration level difference have been calculated at some frequency points. Therefore, in the design process of the impedance-balanced foundation, it is necessary to combine the excitation load characteristics of the equipment with adjusting the panel thickness.

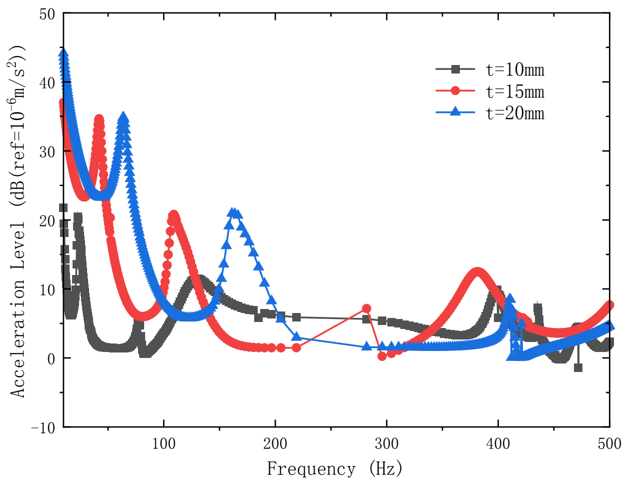


Figure 8. Average vibration level difference curve of assessment points with different thicknesses of foundation panels.

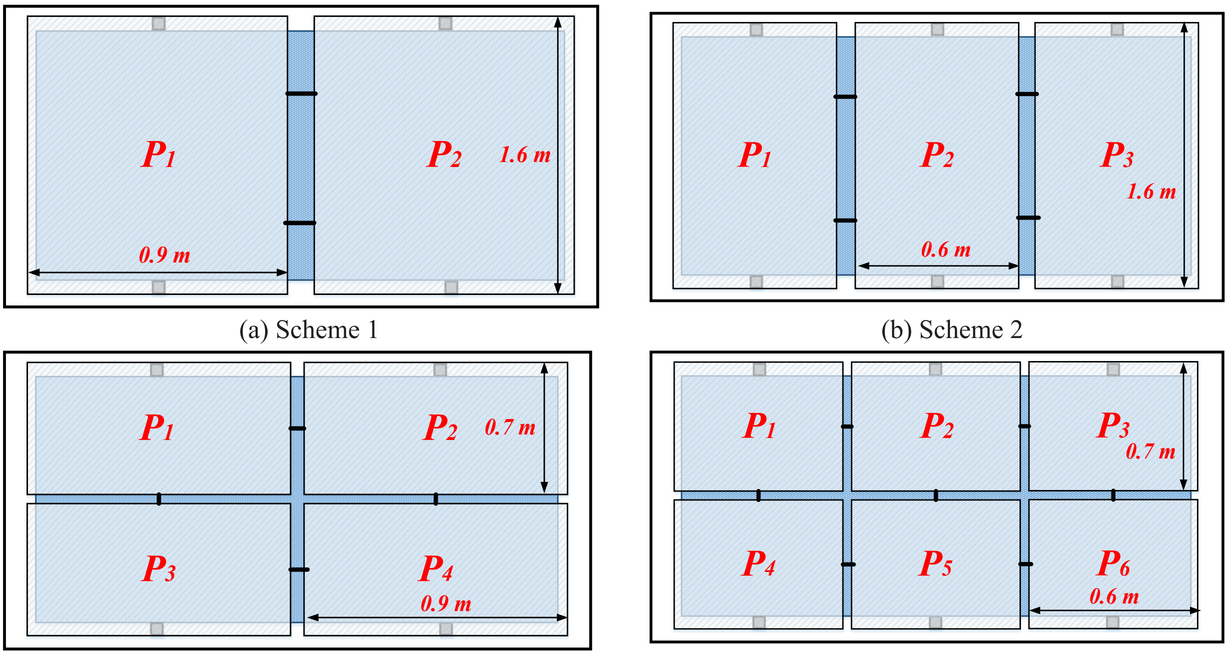
The Influence of Panel Layout on the Vibration Isolation Characteristics of the Impedance-balanced Foundation

With a reasonable discussion of the foundation panel, the elastic waves in the response plane of the panel can be effectively isolated and controlled, thus effectively increasing the vibration reduction and isolation level of the foundation. To investigate the influence of panel layout on the vibration characteristics of impedance-balanced foundation, taking the four layout schemes shown in Table 3 and Figure 9 as examples, the vibration response of the foundation under different panel layout modes was calculated, and the calculation frequency band and loading method were the same as the previous text.

The comparison of the vibration response and vibration level difference of different schemes of the foundation is shown in Figures 10-11. It can be seen that in the 10-500 Hz frequency band, after disassembling the foundation panel, the vibration isolation characteristics of the foundation will change. In the 10-500 Hz analysis frequency band, Scheme 4 causes the lowest level of structural vibration response. In each scheme, as the number of sub-panels increases, the number of peaks in the response curve will decrease, and the curve has a tendency to shift towards high frequencies. From the vibration level difference curves of each scheme, it can be observed that Scheme 1 has a higher vibration isolation effect at 10-100 Hz, the average isolation level is about 10 dB.

Table 3. Size parameters of fluid-filled sac under different layout schemes of the foundation.

Disassembly scheme	Number of panels/piece	Single foundation panel size/m
Scheme 1	2	0.90 × 1.60
Scheme 2	3	0.60 × 1.60
Scheme 3	4	0.90 × 0.70
Scheme 4	6	0.60 × 0.70



(a) Scheme 1 (b) Scheme 2

(c) Scheme 3 (d) Scheme 4

Figure 9. Schematic diagrams of different layout schemes for the foundation panel.

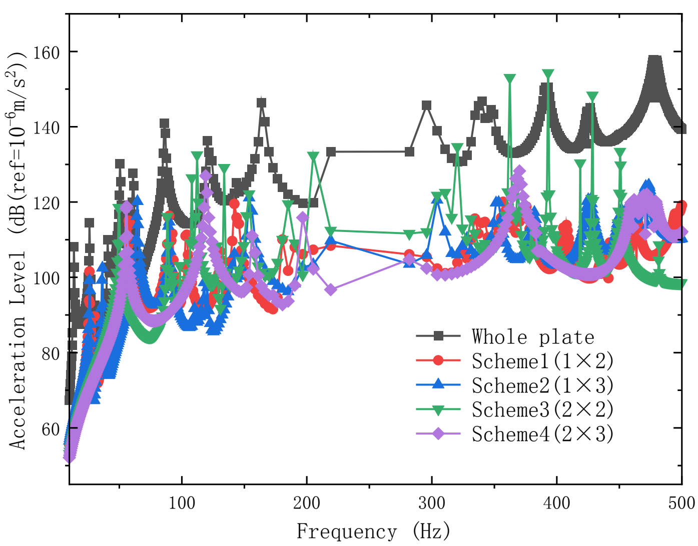


Figure 10. Average vibration acceleration level curve of the bottom plate with different layout schemes of the foundation panel.

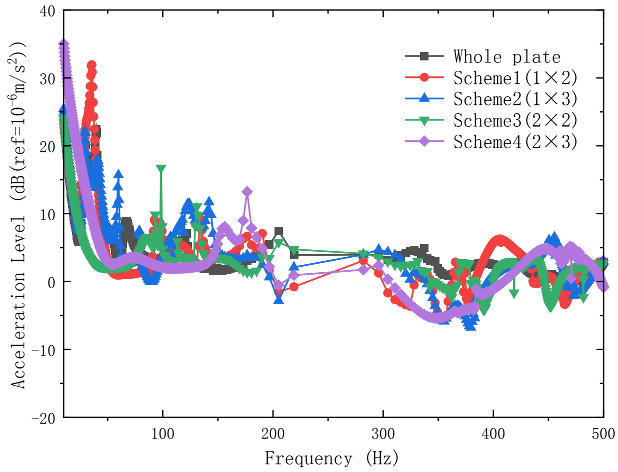


Figure 11. Vibration level difference curve of assessment points with different layout schemes of foundation panels.

4.2 Influence of Foundation Panel Connection Stiffness

To investigate the influence of the stiffness of the foundation panel connection on the vibration reduction and isolation characteristics of the foundation, based on the foundation model of Scheme III mentioned above, the average vibration acceleration level of the foundation plate was calculated when the hinge stiffness between the foundation panels was 500 N·m^2, 1000 N·m^2 and 1500 N·m^2, respectively. The calculation results are shown in Figures 12-13.

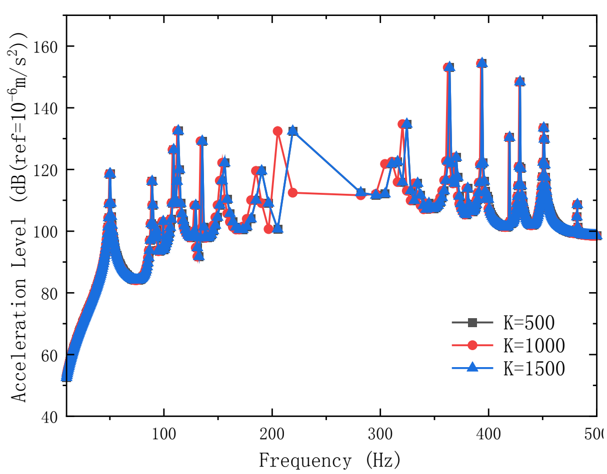


Figure 12. Average vibration acceleration level curve of the foundation plate with different connection stiffness of the foundation panel.

From Figures12-13, it can be seen that in the frequency band of 10-500 Hz, when the stiffness of the hinge connections among the panels increases, the acceleration response curves of each structure remain basically consistent, and the frequencies corresponding to the positions with larger responses in the curves remain basically unchanged. The maximum isolation level in the frequency range of 10-500 Hz is 25 dB. This is because the increase in the stiffness of the connections between the foundations has a limited effect on the overall natural character of the foundations. The lower the stiffness, the more pronounced the oscillation of the vibration level difference curve in the frequency band. However, as the stiffness increases, the change in the vibration level difference curve is relatively stable.

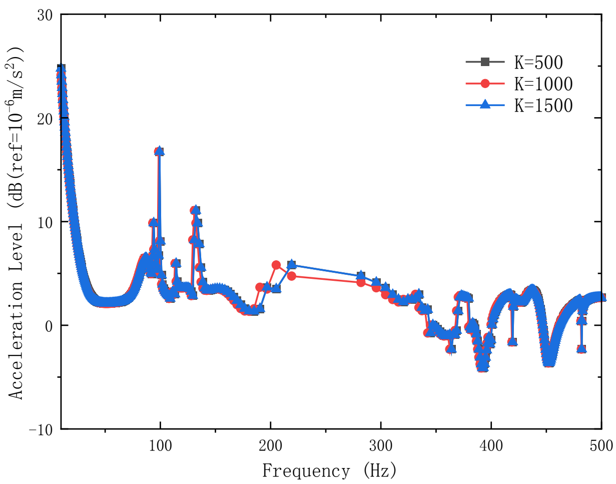


Figure 13. Average vibration acceleration level difference curve of foundation panel with different connection stiffness.

4.3 The Vibration Isolation Property of the Impedance-balanced Foundation Subjected to White Noise Excitation

Using white noise excitation in the calculation of isolation performance is of significant importance. White noise excitation is a signal with constant average power spectral density across all frequencies. By containing components of various frequencies, the use of white noise excitation allows for a more comprehensive evaluation of the performance of the isolation system, providing a valuable reference for isolation design and optimization. Therefore, this paper conducts the calculation of impedance-balanced foundation isolation performance under white noise excitation based on the aforementioned model. The calculation results are shown in Figure 14.

From Figure 14, it can be observed that the impedance-balanced foundation isolation performance, under white noise excitation, exhibits a similar curve trend to that under unit force excitation. Both show effective isolation in the frequency range of 10-150 Hz, with maximum isolation of 18 dB at 100 Hz. However, the isolation effectiveness is weaker in the frequency range greater than 300 Hz. Therefore, it can be concluded that the impedance-balanced foundation possesses favorable low-frequency isolation performance.

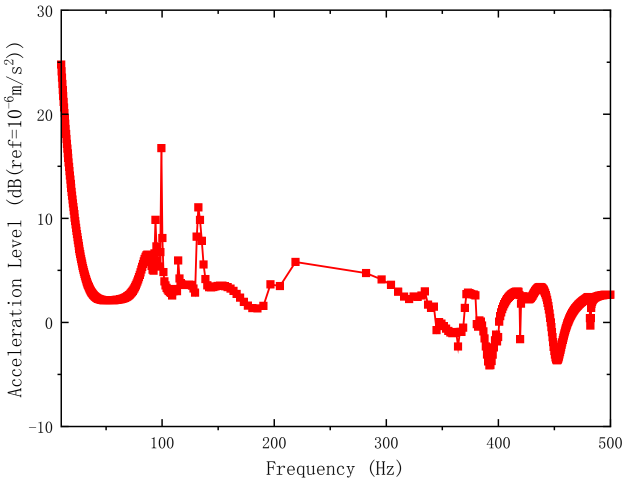


Figure 14. Average vibration acceleration level curve of the foundation plate with different connection stiffness of the foundation panel.

5. Conclusions

This paper proposes a vibration reduction method based on the principle of impedance balancing and designs an impedance-balanced foundation with a "discontinuous panel-vibration isolation liquid layer-foundation structure". Based on the structure-acoustic coupling finite element method, the vibration reduction characteristics of the impedance-balanced foundation under unbalanced excitation of the equipment are studied, and the influence of the structural parameters of the foundation panel on its vibration reduction characteristics is explored. The main conclusions are as follows:

(1) The vibration level difference of the impedance-balanced foundation is higher than that of the traditional foundation with 10 dB in the low-frequency band of 10-500 Hz subjected to the combined action of unbalanced excitation force and moment.

(2) The thickness and quantity of the panel have an influence on the isolation performance of the impedance-balanced foundation. Furthermore, the impedance-balanced foundation exhibits superior vibration isolation performance within the low-frequency range of 10-150 Hz. When the number of sub-panels is 4 and the arrangement is 2 * 2, the isolation performance of the foundation is better among the four layout schemes considered in this paper. The effect of panel connection stiffness on the isolation performance of the foundation is not obvious.

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Data Availability Statement

The data used to support the findings of this study are included within the article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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