

Effects of a breakwater on a floating solar farm in heading and oblique waves

Detai Zou^{a,b,1} (邹德态), Yujia Wei^{b,1} (魏宇嘉), Binjian Ou^b (欧锦鑑), Chao Zhang^{a,*} (张超)
 Shengnan Chu^{a,b} (褚胜男), Luofeng Huang^{b,*} (黄洛枫)

^aSchool of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China

^bFaculty of Engineering and Applied Sciences, Cranfield University, Cranfield MK43 0AL, UK

Abstract: Floating PhotoVoltaic (FPV) solar farms have gained significant research and industrial interests in recent years. However, to support its deployment in abundant ocean space, FPV is required to be protected against wave loading. Thus the usage of a breakwater in front of a floating solar farm is particularly promising. In this work, a time-domain simulation model for an array of FPV solar units in heading and oblique waves was established. Following validation against experiments, the model was used to predict the wave-induced motion and loading responses of each floating solar unit in an array, first without a breakwater, and subsequently with a breakwater. By comparison, it was found that a breakwater can reduce the wave-induced motions of a floating solar farm by up to 56%, alongside up to 55% reduction of loading on the joints between FPV units. However, the breakwater is less effective in relatively long waves and could induce some increase of loading on joints, signifying future work to optimise the design of the breakwater based on the intended environmental condition. Overall, the present results provide insights into a practical breakwater solution for FPV in offshore and coastal conditions, supporting the long-term development of this industry.

Keywords: Floating Solar, Ocean Waves, Motions, Loading on Joints, Breakwater, Simulation.

1. Introduction

Solar PV, as the most affordable clean energy method, has been increasingly favored in recent years [1]. However, the placement of solar panels on land can lead to conflicts with resource conservation, human activities, agricultural developments, and so on [2]. The issues also cannot be avoided by installing solar panels on bodies of freshwater, such as artificial lakes, natural lakes, and abandoned mining lakes [3-4], although it was found that the efficiency of photovoltaic systems can be enhanced to some extent due to the cooling effect of water [5-12]. In this context, the industry is motivated to deploy FPV systems in coastal and offshore regions to utilise the abundant ocean space [13]. However, the intricate sea conditions present challenges to the design of FPV systems, such as the requirement to endure extreme environmental events and fatigue on joints and

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¹These authors have made equal contributions and share the first authorship.

*Corresponding authors: zhangchao@ujs.edu.cn (C. Zhang); luofeng.huang@cranfield.ac.uk (L. Huang).

connections [14]. The research needs to address the response of FPV systems in marine environments with loads from waves.

When maritime structures collide with water waves, complex interactions occur between them. Behera et al. [15] conducted a study looking into the interaction between oblique waves and a floating elastic plate that serves as an effective breakwater. Selvan and Behera [16] investigated the impact of a gravity wave on a circular elastic floating permeable membrane by using linear water wave theory in both homogeneous and two-layer fluids, while Gayathri et al. [17] examined the impact of porosity in dampening the far-field wave amplitude in a scattering of incoming waves. Similarly, Hossain et al. [18] examined how the larger uniform mass and structural rigidity of a floating elastic plate influence the flow beneath it and found that structural rigidity has no effect on the flow stability in the case of inviscid flow, while larger uniform mass stabilizes the growing disturbance generated due to the externally imposed shear at the surface of the plate. Liu and Wang [19] investigated the wave-attenuation performances and hydrodynamics of moored box-type floating breakwaters with six different cross-sections. The considered parameters included breakwater density, immersion depth, ballast-water gravity, and wave condition. It was revealed that the performance of floating breakwaters is significantly influenced by immersion depth and wave conditions; however, it is minimally affected by density and ballast-water gravity.

Loukogeorgaki et al. [20] evaluated the internal forces of connectors in a pontoon-type modular floating breakwater system consisting of flexibly connected and moored chain modules. Each connector in their study was made of coated wire rope, and its flexibility was expressed by the axial and bending stiffness. Zhao et al. [21] proposed a general approach to determine the stiffness configuration for various wave conditions by simplifying the connector and ignoring its torsional and bending stiffness. It was indicated that the combination of small longitudinal stiffness, large transversal, and large vertical stiffness is favourable for motion under most wave conditions. Xia et al. [22] applied a control method in conjunction with hinged connectors to suppress the heave, roll, and pitch motions of a five-modular floating structure. Their numerical simulations confirmed the efficiency of combining the control strategy with hinge connections. Ma et al. [23] examined the dynamic behaviours of a hinged two-body floating aquaculture platform under regular waves and it was shown that the hinge-joint rotational stiffness has a predominant influence on the maximum pitch response.

Among the different types of connection constraints, hinge joints are frequently utilised connectors in large arrays to limit the relative motion between adjacent modules. Several studies have been conducted to showcase the accurate prediction of motion response for each floater in a hinged multi-body system. Newman [24] was the first to consider hinge constraints in multi-body problems. He utilised a mode generalising method to predict the vertical motion and relative rotation of a hinge in a two-barge system.

Sun et al. [25] applied the Lagrange multiplier technique to investigate the same interconnected barge configuration. They compared their numerical findings with those of Newman [24] and achieved a good agreement. Ren et al. [26] investigated the effects of various combinations of hinges, linear pitch springs, and

linear pitch dampers on the shear force, bending moment of connectors, and the motion of modules. Their findings indicated that using a hinge-PTO-type design for the outermost connector can effectively reduce the motion of the outermost module. Jiang et al. [27] employed a potential-flow-based numerical model to investigate the hydrodynamic sensitivity of an articulated modular floating structure. Their findings indicated that while the hydrodynamic characteristics were consistent across arrays of varying module numbers, the translational horizontal motions were highly responsive to the incident wave angle. Liu et al. [28] conducted numerical simulations to analyze the hydrodynamic responses of a novel hybrid modular floating structure array. The results demonstrated that this hybrid system showed good longitudinal expansibility for mild marine environments. Bispo et al. [29] developed a numerical model to examine the interaction of waves with a set of hinged plates and they found that the rotational stiffness of the hinges greatly affects the vertical displacement of the structure. In the existing literature, the research on the motion response of multi-body array structures comprised of small modules under oblique wave conditions is extremely limited, and the connection loads of the floaters are still unclear in such cases [30-32].

Previous work of simulating wave-structure interactions has a branch based on the potential flow theory, although this introduces inaccuracy due to the exclusion of the viscosity, the approach is still widely used in the dynamic analysis of floating structures in waves. The exclusion of fluid viscosity can be remedied by adding a damping term. For example, Cao et al. [33] used the ANSYS-AQWA software to simulate the movement response of float-over barges, topsides and platforms in an ocean environment. The authors added an external linear damping factor to mitigate the energy dissipation difference caused by missing viscosity. Cutajar et al. [34] analyzed the wave attenuation performance of different box-type, floating breakwater structures by using the potential flow solver AQWA. They used a damping cap method to effectively correct the effect caused by the exclusion of fluid viscosity. Yang and Yu [35] investigated a floating solar photovoltaic (FPV) FPV system by numerical and experimental simulations under wave and wind loads to analyze the motion characteristics of the platform based on ANSYS AQWA and ANSYS FLUENT. Lin and Yang [36] implemented the software ANSYS AQWA to discuss the hydrodynamic analysis of the DeepCwind semi-submersible floating platform in waves based on the potential flow theory by considering the second-order wave exciting force. The simulation of a floating solar farm involves a large number of floating bodies, which would be too computationally expensive to use a higher-order approach, such as CFD. The approach with damping enhances the potential flow theory to achieve a balance between computational costs and accuracies, offering a practical for simulating floating solar farms.

To ensure the reliability of modular arrays and reduce the maintenance costs, it is necessary to install connectors between modules to mitigate the risks of collision and drift. Fu et al. [37] studied the hydroelastic response of a flexible floating interconnected structure, considering translational and rotational stiffness using a comprehensive hydroelastic theory that incorporates hinge rigidity modes. Michailides et al. [38] numerically studied the internal loads of a modular pontoon-type floating structure consisting of flexible floating modules (pontoons) connected by flexible connectors. Diamantoulaki and Angelides [39] conducted a performance

comparison of various configurations of hinged floating breakwaters against a single floating breakwater without hinges. Their results demonstrated that increasing the number of hinge joints could enhance the effectiveness of the floating breakwaters, except for extremely low frequencies and high frequencies. This limitation was attributed to the relatively small dimensions of the array in comparison with the corresponding wavelengths at low frequencies, as well as to low response levels in the short waves.

The aforementioned research inspired the idea of installing a breakwater upstream of a floating solar farm to mitigate the wave impacts, the idea of combining breakwaters with floating solar farms (FPVs) has been previously discussed [40]. Thus, this study establishes a computational model to simulate the fluid-structure interactions of a floating solar farm in various wave conditions, focusing on the effect of a breakwater. The novelty of this work is that a breakwater is considered together with FPV, and its effect on each unit of floater in the solar farm is analyzed. The results include hydrodynamic motion coefficients that indicate the motion of each solar unit in an FPV array, as well as wave loading on the connections between the units. Based on these results, the effects of the breakwater are analyzed through a comparison between cases with and without it, and the practical implications of the research are discussed.

The structure of this paper is organized as follows: Section 2 outlines the modularized solar farm concept and introduces the computational models and the theoretical equations underlying. Section 3 presents a series of verification and validation for the developed model. In Section 4, we compared the responses of the FPV array under the same wave conditions with and without the breakwater to study the effects brought about by the breakwater. The paper concludes in Section 5 with recommendations for future work.

2. Computational approach

2.1 Model of a floating solar farm

A simulation model for the design of an FPV system, using the AQWA software, is described here. The array consists of a multi-module array structure arranged in 13×7 configuration. The coordinate system and FPV array are illustrated in Fig.1. The global coordinate system is denoted as $O-XYZ$, with the $O-Z$ axis pointing upward. Hinged connections are employed between the floaters along the $O-X$ direction, with the hinge joint axis parallel to the Y -axis, allowing only relative rotation between structures. In the $O-Y$ direction, linear cables and fenders are used for soft connections to prevent local contact.

The assumptions encompass dimensionless geometric properties of these mechanical connections and the absence of added mass from the connections. The incident wave direction β is the angle between the wave propagation direction and the X -axis. Each floater has dimensions of 1.6 m in length, 1.1 m in width, and a fixed draft of 0.1 m. The model focuses on semi-submersible floaters on the free water surface, excluding the supporting structure for the solar panels. The specific model diagram is shown in Fig.2. The floating bodies are made of foamed polyethylene with a density of approximately 512 kg/m^3 [30].

The gap between adjacent floaters considers the size of the floaters, relative motion, and the resonance effect of solitary waves in narrow slots, with an initial positioning of 0.1 m. The mooring modules adopts a tension-leg mooring, consisting of four linear elastic cables. This cable is a basic form of tension-only spring, where the tension is directly proportional to its extension, with the constant of proportionality designated as stiffness. Each cable projection angle with the X - Y plane is 45° , simulating a water depth of 5 m. The mooring chains are assumed to be steel, the hinges are assumed to be stainless steel, and the fenders are assumed to be polyethylene. Their standard stiffnesses are found from [30]. The general design parameters of the selected floater and mechanical connections are presented in Table 1.

The current simulations contain a large amount of floating bodies connected, which could be computationally prohibitive to use high-order CFD. For example, Delacroix et al. [41] only studied 16 floaters using STAR-CCM+ and their interaction with waves. As an alternative potential flow theory offers significant computational efficiency, especially when dealing with large-scale problems. Many researchers have employed potential flow theory for similar problems and achieved reliable results. For example: Smith et al. [42] used potential flow theory in their study on the impact of breakwaters on wave attenuation and validated their simulation results through experiments. Wang and Kim [43] adopted a similar approach in their study of the wave response of floating structures, and their results showed a high degree of agreement with experimental data. Potential flow solvers, such as AQWA, can simulate inviscid fluid dynamics. However, their limitations include an inability to simulate viscous effects, complex flow phenomena, and difficulties in handling complex boundary conditions. The potential flow theory used does not account for nonlinear wave-structure interactions, the wave height is constant in the study which may not capture the full range of real-world conditions. This study incorporates an additional damping term in the simulation, the damping values were determined using empirical formulas and pertinent literature [44][45], and viscous damping was primarily added to the heave response (z -direction) of the array. The specific value of the viscous damping coefficient was set to 15% of the floater's mass. By adding the damping term, the solver can more accurately simulate the dynamic response of the floating solar farm under heading and oblique wave conditions, particularly considering the influence of viscous effects on array motion and energy dissipation. This approach largely reduces the computational costs compared to CFD, whilst offering improved reliability for the results.

Regarding the selection of parameters for time-domain analysis, simulations are conducted for regular waves with four different wave periods and different wave directions. The focus is on extracting the heave and pitch responses of the floaters, as well as the moment on the hinges in the region with significant responses. The average values of heave and pitch amplitudes are obtained, along with the moment on the hinges at all time steps.

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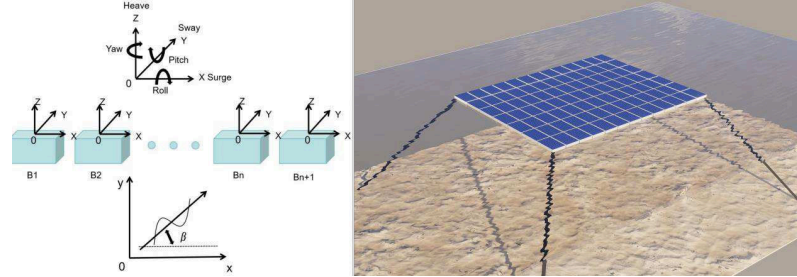
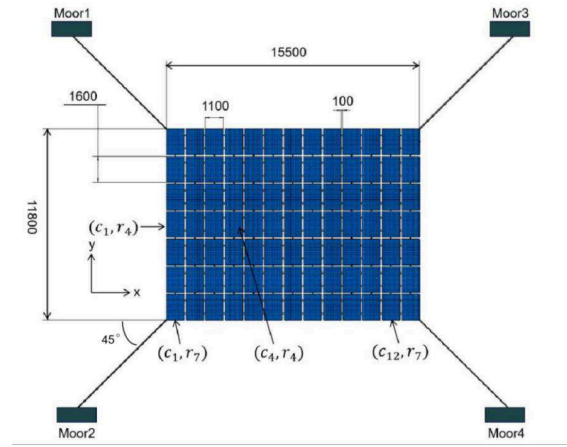
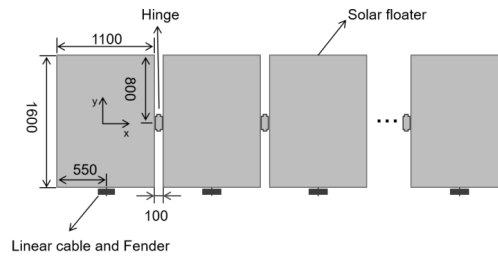


Figure 1. Coordinate systems of the FPV array (X, Y, Z, RX, RY, RZ represent six degrees of freedom, and the corresponding motions are surge, sway, heave, roll, pitch, and yaw). The X - Y plane is the horizontal plane, and the wave direction is the angle β between the wave and the X -axis.



(a)



(b)

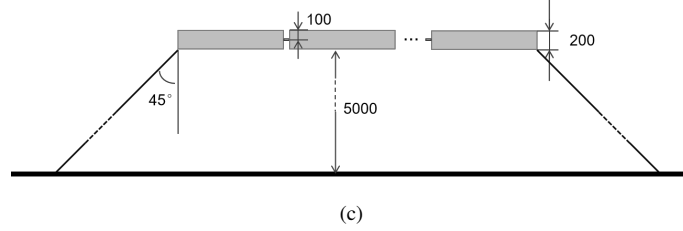


Figure 2. Numerical model of the FPV arrays. (c_x, r_y) means the floater in column x and row y . (a)(b) top view, (c) side view. Unit: mm.

Table 1. Physical properties of the selected floater and mechanical connections.

Floater		Mechanical connections	
Length	1.6m	Mooring stiffness	1e7 N/m
Width	1.1m	Cable stiffness	5e6 N/m
Height	0.2m	Fender stiffness	5e6 N/m
Draft	0.1m		
Gravity	9.81m/s ²		
I _x	38.13kg.m ²		
I _y	18.33kg.m ²		
I _z	55.293kg.m ²		

2.2 Fluid solution

Assuming the surrounding fluid is ideal, according to the linear potential flow theory, the velocity potential can be decomposed into incident potential, diffracted potential, and radiated potential [46].

$$\phi(x, y, z, t) = \phi_I(x, y, z, t) + \phi_D(x, y, z, t) + \phi_R(x, y, z, t) \quad (1)$$

In the equation, ϕ_I represents the incident wave velocity potential, ϕ_D is the diffracted potential, and ϕ_R is the radiated potential. Each of these velocity potential components can be determined by solving the Laplace equation based on the corresponding boundary conditions.

Using linear airy wave theory, assuming the incident wave is a plane wave with a single frequency and a single direction, its incident potential can be expressed as:

$$\varphi_I = \frac{ig\xi_A}{\omega} \frac{\cosh \cosh z+H}{\cosh \cosh kH} e^{-ik(x \cos \cos \beta + y \sin \sin \beta)} \quad (2)$$

where: ξ_A is the wave amplitude of the incident wave. β is the wave direction angle, representing the angle between the wave propagation direction and the positive X -axis. H is the water depth; g is the acceleration due to gravity. k is the wave number, i is the number of modes, satisfy the dispersion relation: $\omega^2 = gk \tanh \tanh kH$.

2.3 Structural solution

After the total velocity potential is obtained, the linear Bernoulli formula can be used to calculate the dynamic pressure distribution on the surface of each floater. The surface dynamic pressure distribution of the m -th floater is:

$$P = -\rho \frac{\partial \phi}{\partial t} | S^{(m)} = i\omega \rho \varphi | S^{(m)} e^{-i\omega t} = i\omega \rho (\varphi_I + \varphi_D + \varphi_R) | S^{(m)} e^{-i\omega t} \quad (3)$$

Therefore, the total fluid force received is:

$$\vec{F} = -\iint_{S^{(m)}} p \vec{n}^{(m)} dS^{(m)} \quad (4)$$

The wave disturbance force is:

$$\vec{F}_W = \vec{F}_W^k + \vec{F}_W^d = -\iint_{S^{(m)}} i\omega \rho (\varphi_I + \varphi_D) e^{-i\omega t} \vec{n}^{(m)} dS^{(m)} \quad (5)$$

where, $\vec{F}_W^k = -\iint_{S^{(m)}} i\omega \rho \varphi_I e^{-i\omega t} \vec{n}^{(m)} dS^{(m)}$ is the Froude-Krellov force, which is the wave force obtained without considering the influence of the object on the incoming wave flow field; $\vec{F}_W^d = -\iint_{S^{(m)}} i\omega \rho \varphi_D e^{-i\omega t} \vec{n}^{(m)} dS^{(m)}$ is the diffraction force; $\vec{n}^{(m)}$ is the vector in the outer normal direction of the wet surface of the m -th floater.

The radiant force of the i -mode motion of the m -th floater is:

$$\begin{aligned} \vec{F}_W^k &= -i\omega \rho e^{-i\omega t} \iint_{S^{(m)}} \varphi_R \vec{n}^{(m)} dS^{(m)} \\ &= i\omega \rho e^{-i\omega t} \iint_{S^{(m)}} \sum_{l=1}^M \left[\left(\sum_{j=1}^6 \zeta_j^{(l)} \varphi_j^{(l)} \right) \vec{n}_l^{(m)} \right] dS^{(m)} \\ &= \omega^2 \rho e^{-i\omega t} \iint_{S^{(m)}} \sum_{l=1}^M \left[\left(\sum_{j=1}^6 \zeta_j^{(l)} \varphi_j^{(l)} \right) \vec{n}_l^{(m)} \right] dS^{(m)} \\ &= \omega^2 e^{-i\omega t} \sum_{l=1}^M \left[\sum_{j=1}^6 \zeta_j^{(l)} \left(\mu_{ij}^{(ml)} + \frac{\lambda_{ij}^{(ml)}}{i\omega} \right) \right] \end{aligned} \quad (6)$$

$$\text{where } \mu_{ij}^{(ml)} + \frac{\lambda_{ij}^{(ml)}}{i\omega} = \rho \iint_{S^{(m)}} \varphi_j^{(l)} \vec{n}_l^{(m)} dS^{(m)} \quad i, j = 1, 2, 3 \dots 6; \quad m, l = 1 \dots M \quad (7)$$

$\mu_{ij}^{(ml)}$ and $\lambda_{ij}^{(ml)}$ are the added mass and damping coefficient in the i -th direction of the m -th floater induced by the j -th mode motion of the l -th floater.

In addition to radiation and diffraction forces, the floater in the wave is also subject to the static water recovery force caused by deviation from the equilibrium position. The hydrostatic recovery force is generated only in the vertical direction (heave, roll and pitch). The expression for the restoring force of still water can be written as:

$$P_s(x_b, y_b, z_b, t) = -\rho g(z_b + x_3(t) - x_b x_5(t) + y_b x_4(t)) \quad (8)$$

where (x_b, y_b, z_b) are the center of buoyancy coordinates, and relative to the floater coordinate system, $x_3(t), x_4(t), x_5(t)$ are heave, roll and pitch, respectively.

Based on Newton's second law, the motion equation of free floaters in the frequency domain can be expressed as [47]:

$$[-\omega^2 M_q - i\omega B + K]\{\eta\} = \{F\} \quad (9)$$

where M_q, B , and K are the mass, damping, and stiffness matrix, respectively; η is the displacement matrix; and F is the external forces matrix, which includes the wave excitation force F_W , and the hydrodynamic forces F_R . It should be noted that the structure damping is assumed to be zero in this study. By rearranging the equation and shifting the hydrodynamic forces to the left of the motion equation, the equation can be expressed as:

$$[-\omega^2 (M_q + \mu) - i\omega \lambda + K]\{\eta\} = \{F_W\} \quad (10)$$

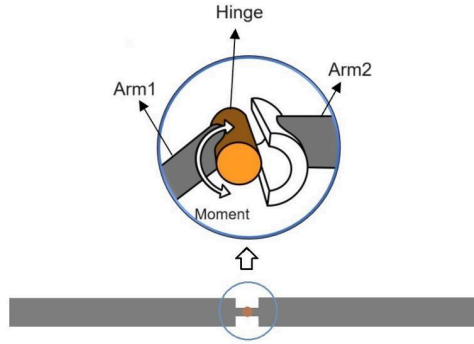


Figure 3. Schematic diagram of hinge and bending moment.

If a hinge constraint along the Y -axis is applied between two bodies, the displacements in five DOFs (surge, sway, heave, roll, and yaw) are continuous at the hinge joint and the pitch motion is free. There are thus five constraints between two interconnected m -th and $m+1$ -th bodies, and the corresponding constraint equations are:

$$\begin{aligned} \eta_1^m + \eta_5^m z^m - \eta_6^m y^m &= \eta_1^{m+1} + \eta_5^{m+1} z^{m+1} - \eta_6^{m+1} y^{m+1} \\ \eta_2^m - \eta_4^m z^m + \eta_6^m x^m &= \eta_2^{m+1} - \eta_4^{m+1} z^{m+1} + \eta_6^{m+1} x^{m+1} \\ \eta_3^m + \eta_4^m y^m - \eta_5^m x^m &= \eta_3^{m+1} + \eta_4^{m+1} y^{m+1} - \eta_5^{m+1} x^{m+1} \end{aligned}$$

$$\begin{aligned}\eta_4^m &= \eta_4^{m+1} \\ \eta_6^m &= \eta_6^{m+1}\end{aligned}\quad (11)$$

where (x^m, y^m, z^m) and $(x^{m+1}, y^{m+1}, z^{m+1})$ are the coordinates of a hinge joint in the m -th and $m+1$ -th body-fixed coordinate systems, respectively. Similarly, if the hinge constraint is applied along the X -axis, then only the roll motion is free. The dynamic equation of motion for the hinged multi-body array in the frequency domain can be written as:

$$\left[-\omega_0^2(M_q + \mu) - i\omega_0\lambda + K D_f^T D_f 0 \right] \{\eta F_f\} = \{F_W 0\} \quad (12)$$

where M_q and K are the array mass and stiffness matrix of $(6N \times 6N)$, respectively; μ and λ are the array added mass and potential damping matrix of $(6N \times 6N)$; D_f is the displacement constraint matrix of $(Q \times 6N)$, in which Q represents the number of hinge joint constraints; η is the frequency-dependent displacements matrix of $(6N \times 1)$; F_f is the joint force vector of $(Q \times 1)$; and F_W is the wave excitation force array of $(6N \times 1)$.

Dynamics of floating multiple rigid bodies in the time domain can be represented by Cummins equation as given in [48]:

$$(M + \mu(\infty))\ddot{\xi}(t) + (K + K_E)\dot{\xi}(t) = F_W(t) + F_C(t) \quad (13)$$

where $\mu(\infty)$ is the added mass matrix at infinite frequency, K_E is the external stiffness matrix, $\xi(t)$ is the displacement vector in time domain, while $F_W(t)$ and $F_C(t)$ are the wave excitation and convolution forces in time domain. The upper dot means time derivative of a variable. Assuming that the random waves are linear, which can be generated by the superposition of regular waves, the added mass at infinite frequency, wave-excitation force, and convolution force can be acquired from the following equations:

$$\mu(\infty) = \mu(\omega) + \int_0^\infty R(t) \frac{\sin \omega t}{\omega} dt \quad (14)$$

$$F_C(t) = - \int_0^\infty R(\tau) \dot{\xi}(t - \tau) d\tau \quad (15)$$

$$R(t) = \frac{2}{\pi} \int_0^\infty B(\omega) \cos(\omega t) d\omega \quad (16)$$

$$F_W(t) = \text{Re}(\sum_{j=1}^N \xi_{A,j} L(\omega_j) e^{-i(k_j x - \omega_j t - \alpha_j)}) \quad (17)$$

where $R(t)$ is the retardation function, which is Fourier cosine transform of the radiation damping $B(\omega)$, $L(\omega_j)$ is linear wave excitation at j -th frequency, while α_j is phase angle. When M bodies are involved, since each body has 6 DOF motions, the total matrix size for the mutual hydrodynamic interaction is $6 \times M$ by $6 \times M$.

Mooring system

In the generalized coordinate, r denotes the position vector, which is a function of arc length s and time t in order to define space curve, r' represents the unit tangent vector to the space curve, while r'' and $r' \times r''$ are the principal normal and bi-normal vectors, respectively.

The equation of motion, which includes the line's tension and bending effects, is presented as:

$$-(Elr'')'' + (\tilde{\lambda}_L r') + q_D = m_D \ddot{r} \quad (18)$$

where E and I are Young's modulus and the second moment of area, $\tilde{\lambda}_L = \tilde{T} - EI\kappa^2$ ($\tilde{T}$ is effective tension and κ is local curvature), while q_D and m_D represent the distributed load and the mass per unit length.

As a line is assumed to be extensible and its extension is small and linear, the following condition can be derived:

$$\frac{1}{2}(r' \cdot r' - 1) \approx \frac{T}{EA_T} \approx \frac{\lambda_L}{EA_T} \quad (19)$$

where $A_T = A_E - A_I$ (A_E and A_I is the external and internal cross-sectional area), T is the tension, and $\lambda_L = (T - EI\kappa^2)$ is the Lagrange multiplier.

If the hinged boundary condition is assumed between the floaters and mooring lines, values of sufficiently large translational and negligible rotational stiffness can be implemented. The external force vector induced by linear and rotational springs from a mooring line to the floaters can be expressed as:

$$\tilde{F}_S = \tilde{K}(\tilde{T}_C \tilde{u}_R - \tilde{u}_C) \quad (20)$$

where $\tilde{K}$ denotes the coupling stiffness matrix, $\tilde{T}_C$ is the transformation matrix between the rigid body's origin and the connection position, while $\tilde{u}_R$ and $\tilde{u}_C$ represent the displacement vectors of the rigid body and the connecting location.

Cable and fender elements

The linear elastic rod is defined by the combination of line and fender modules, which provides axial stress and stiffness from stretch and compression. The line $F_{k, \text{line}}$ and fender forces $F_{k, \text{fender}}$ can be calculated as:

$$F_{k, \text{line}} = \begin{cases} K_l(L_l - L_{l0}) & \text{if } L_l > L_{l0} \\ 0 & \text{if } L_l \leq L_{l0} \end{cases} \quad (21)$$

$$F_{k, \text{fender}} = \begin{cases} K_f(L_f - L_{f0}) & \text{if } L_f > L_{f0} \\ 0 & \text{if } L_f \leq L_{f0} \end{cases} \quad (22)$$

where, K_l and K_f are the stiffness of the line and fender, respectively; L_l and L_{l0} denote the instantaneous and unstretched length of the linear cable, similarly L_f and L_{f0} represents the length of fender element.

2.4 Free surface modelling

In a constrained space, like the gap between two vessels, resonance may arise when the incident waves exhibit a particular frequency. Zhao et al. [49] proposed that the linear gap response may be substantially smaller than the second harmonic component, which is strongly driven by the quadratic coupling of the linear terms from the incident wave and occurs in the gap resonant modes. This concept of resonant behavior is also explored by Zhang et al. [50], who found that when the gap between patches aligns with specific wavelengths, the water trapped between them resonates, resulting in amplified oscillations. Interestingly, they also discovered that if both the patches and the water body reach resonance simultaneously, the oscillations can be suppressed, particularly for the seaward patch. Such interactions are significantly influenced by patch stiffness and water depth, while the distance between patches appears to have little effect.

Studies based on potential flow theory indicate that the wave damping between two floating bodies is often not accurately considered. This is primarily because potential flow theory neglects the viscosity of the fluid. To address this issue, many researchers have proposed artificially adding damping to correct the model. Chen [45] proposed a "damping-lid" method, which involves adding a term proportional to the fluid velocity in the fluid

dynamics equations. This addition introduces a damping term in the boundary conditions of the free liquid surface to suppress its elevation. The damping coefficient is artificially introduced and should be determined based on the experimental measurements.

After adding the damping term, Bernoulli's equation can be written as:

$$\frac{P}{\rho} + gz + \frac{\partial \phi}{\partial t} + \frac{1}{2}(\nabla \phi)^2 + \varepsilon \cdot \omega \cdot \phi = 0 \quad (23)$$

In the above formula, ω is the natural frequency of the array, ε is the damping coefficient. In this study, an appropriate damping coefficient was determined using an empirical equation from Chen's model [45]. Based on the geometrical dimensions of the cubic structures applied, a damping coefficient of 0.15 was selected, which is close to verified similar research such as [51].

The free liquid surface boundary condition is modified to:

$$-(1 + i\varepsilon)\frac{\omega^2}{g}\varphi_D + \frac{\partial \varphi}{\partial z}\varphi_D = 0, \text{ on } z = 0 \quad (24)$$

3. Verification

Verification of the hydrodynamic performance of multiple unconnected floaters was conducted to ensure accurate modeling of dynamic structural motions in wave-structure interactions. The potential flow model was established using Ansys AQWA, following the detailed configurations consistent with Chen et al. [52] and Chen et al. [53]. The model includes several identical rectangular floaters, as depicted in Figure 4, with parameters summarized in Table 2. These floaters are symmetric along both the x and y axes, and the study considers incident head waves. Each floater's center of gravity is at its geometric center, with mass uniformly distributed. The water depth is 50 meters. Given that head seas ($\beta = 0^\circ$) are the primary wave condition considered, the study focuses on the three modes of motion: surge, heave, and pitch, under various heading wave frequencies.

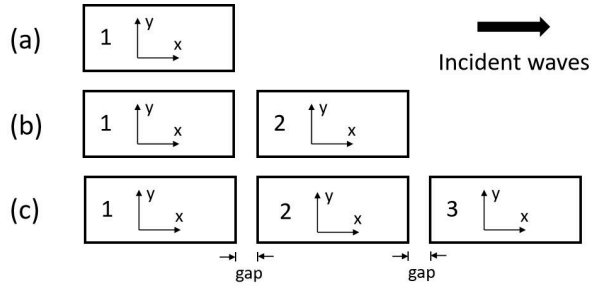


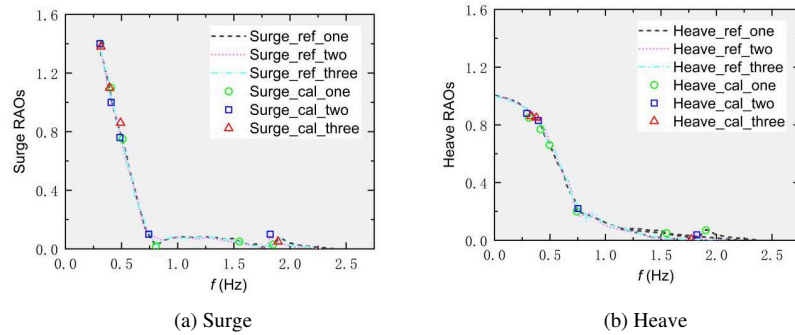
Figure 4: Plan view of three configurations (a) 1 module, (b) 2 modules, (c) 3 modules.

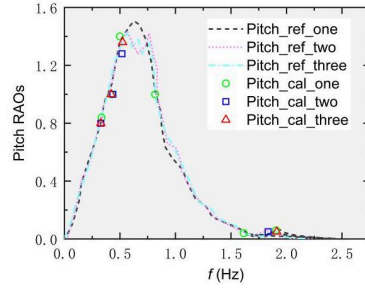
Table 2. Geometrical parameters of a single floater

Module characteristics	Unit	Value
Length	m	100

Breadth	m	50
Depth	m	5
Centre of gravity above base, KG	m	2.5
Draught	m	2
Moment of inertia, I_{xx}	m^4	14.5
Moment of inertia, I_{yy}	m^4	28.9
Moment of inertia, I_{zz}	m^4	32.3

In Figure 5, the Response Amplitude Operators (RAOs) for each windward module of three models (a, b, c) are compared with Chen et al. [54]. Various lines and symbols illustrate the hydrodynamic interactions between different numbers of floaters. The pitch response curves show significant influence from increasing module numbers, with peak magnitudes decreasing from one to three. Displacement results differ, with strong nonlinearity from fluid-structure interactions in short waves causing higher computational deviations. The good agreement between model tests and results shows that potential flow theory is effective for predicting hydrodynamic interactions of multiple structures in waves. However, the inviscid flow assumption requires careful handling of the added damping factor to avoid overestimating interaction effects in some frequency ranges. Table 3 shows the mean deviation between the response amplitudes of the present model and the literature. Numerical errors are higher for pitch motions than for displacement motions due to the rotational motion being affected by changes in the wet surface area, which the Green function method may not effectively calculate.





(c) Pitch

Figure 5: RAOs of the multi-floaters under various wave conditions.

Table 3. Uncertainty evaluations on structural motions.

Uncertainty level	One	Two	Three
Mean surge RAOs	4.6%	3.7%	2.9%
Mean heave RAOs	1.4%	5.2%	6.74%
Mean pitch RAOs	9.5%	9.5%	14.4%

4. Results and discussion

In this section, the numerical model has been extended to hydrodynamic analysis of 13×7 array under various wave conditions. The study focuses on the surge, heave, and pitch motions of each floating solar units. The calculated results are dimensionless, independent of specific sizes or units, facilitating the extrapolation of the findings to different size conditions. For input wave conditions, the wave height is fixed at 0.1 m, R is the ratio of floater length to wavelength L/λ . Although only one wave height is used, RAOs are employed to normalized the results to obtain a ratio of motion responses to the incident wave condition. For results, heave RAOs are nondimensionalized by Z/ζ . Pitch RAOs are nondimensionalized by $\theta/k\zeta$, where θ is rotational angle (rad), ζ is wave amplitude, and $k = 2\pi/\lambda$ is wave number [55]. R_z direction moment is nondimensionalized by $M/\rho g L^2 B \zeta$. Sections 4.1 and 4.2 present results without a breakwater, followed by Sections 4.3 and 4.4 presenting results with a breakwater and its comparison against cases without.

4.1 Heading wave conditions without breakwater

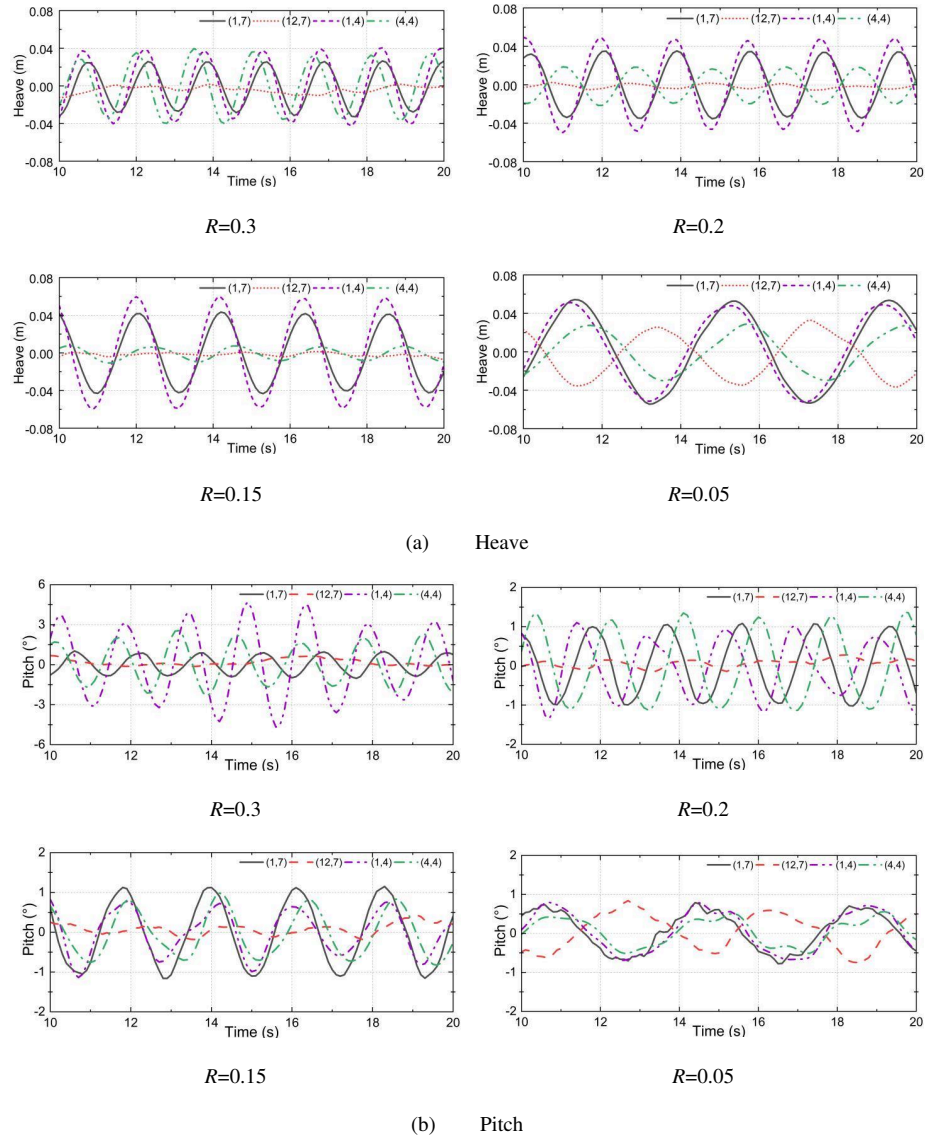


Figure 6. Mechanical response curves of floaters at different positions in the array. (a) and (b) are heave and pitch responses, intercepted 10 s to 20 s in the time domain.

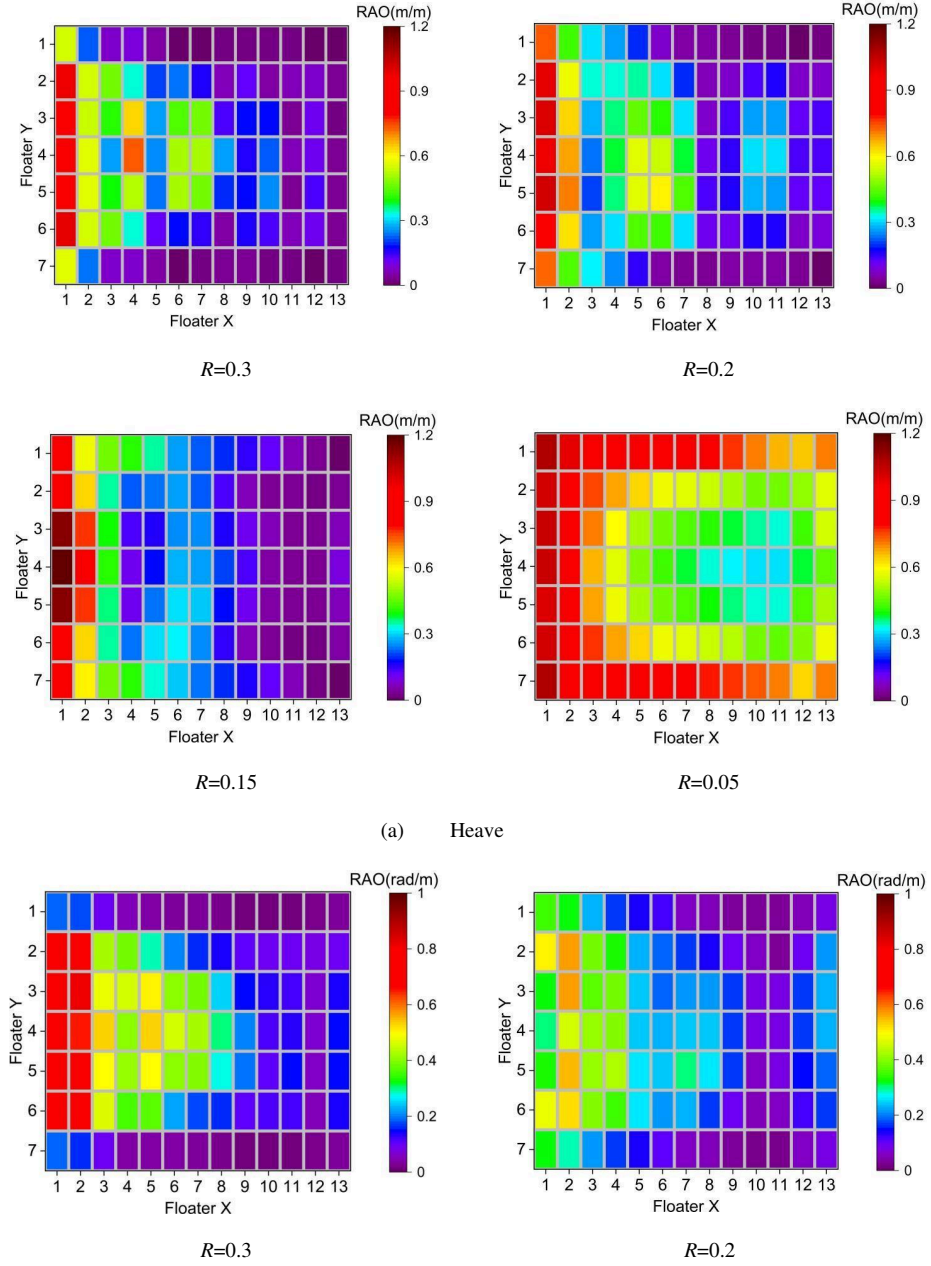
Figure 6 illustrates the mechanical responses of four floaters within the array, focusing on heave and pitch behaviours under different wave periods. Given that the heading wave and the array structure is symmetrical relative to this direction, four representative floaters were chosen: (1,7), (12,7), (1,4), and (4, 4), where (x,y) means column x, row y. This selection allows for a detailed examination of the array's mechanical response based on location and interaction with the waves. The ratio of structure length to wavelength, denoted as R , is used to categorize these periods. The selected wave periods are 1.533s, 1.878s, 2.169s, and 3.98s ($R=0.3, 0.2, 0.15$ and 0.05), assessing the array's performance under different wavelength conditions.

In Fig.6a, the heave response of the floater (1,4) is consistently the largest. This floater is positioned at the front of the array, where it makes initial contact with the incoming waves. The large heave response can be attributed to the floater's direct exposure to wave forces. Although the floater (1,7) is in the same area, its overall heave response is slightly lower, potentially due to mooring constraints that limit its vertical movement. Floater (4,4), located at the front-middle position, demonstrates a pronounced heave response, particularly under wave conditions $R=0.3$ and $R=0.2$. This behaviour may be related to frequency resonance, where certain wave frequencies align with the natural frequencies of the structure, amplifying the heave response. As the wavelength increases, this resonance effect diminishes, leading to a reduction in heave response. On the other hand, the floater (12,7), positioned at the tail of the array, shows a much smaller heave response overall. Its heave increases slightly when the wavelength is larger ($R=0.05$), suggesting that longer waves have a greater transmission ability, allowing them to propagate further into the array without significant dissipation.

In Fig.6b, the pitch response curves exhibit high-frequency oscillations at shorter wavelengths ($R=0.3$). This behaviour likely results from the nonlinear effects of liquid flow and vibrations caused by hinges interacting with wave forces. Notably, floater (1,4) shows the largest pitch response amplitude, reaching up to 4.7 degrees when $R=0.3$, indicating significant pitching due to its position and exposure to wave impacts. However, as the wavelength increases, this response stabilizes, suggesting that longer waves produce less dynamic pitching. The reason is that longer waves introduce a longer restoring time allowing floaters to reach back to their original position and wait for another movement. Similarly, floater (4,4) follows a comparable trend, with larger response amplitudes in shorter waves, indicative of its susceptibility to resonance and wave impact. The pitch response of the floater (12,7) aligns with its heave response, maintaining consistently low response amplitudes. The exception is at large wavelengths ($R=0.05$), where there is a noticeable increase in pitch, likely due to the stronger transmission of longer waves. These observations suggest that the position of the floater within the array significantly impacts its mechanical response to waves. Factors such as mooring constraints, frequency resonance, and wave transmission play critical roles in influencing heave and pitch behaviours.

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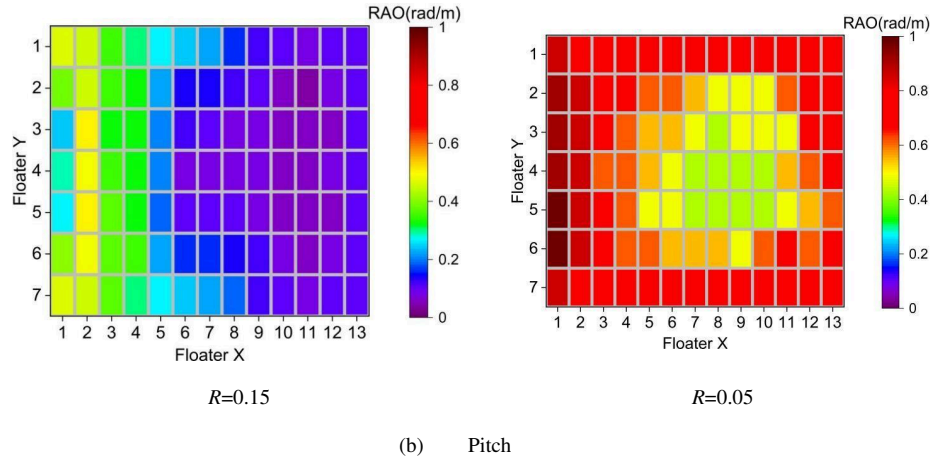


Figure 7. Heave and pitch response of modular array structure. Each color block in (a) (b) corresponds to a floater in column X and row Y .

Figure 7 illustrates the heave and pitch responses of each floater in the array. The RAO values are calculated based on the time-average vertical motion of floaters in the array over 40 seconds. From Fig. 7a, it can be observed that floaters in the front region exhibit the larger heave response (c_1/c_2). When R is 0.3 and 0.2, indicating short wave conditions, the colors in the middle region of the heave response plot appear more chaotic, suggesting that the undulating motion in the middle region of the array structure is more pronounced. Since the penetration ability of short waves is weaker, the undulating region is only observed at the front of the array. When comparing $R=0.2$ to $R=0.3$, the wavelength increases, enhancing wave transmission capability, yet still falls within the realm of higher frequency short waves, resulting in an increase in the undulating region. Additionally, it is seen that the mooring imposes certain constraints on the floaters. Fig. 7b illustrates the pitch response of the array, pitch motion exhibits noticeable fluctuations in the short-wave region ($R=0.3$, $R=0.2$), while under long wave conditions ($R=0.15$, $R=0.05$), it demonstrates a decreasing trend from the frame region towards the central region. Similar to the heave response, the pitch RAO values of the floating structure tend to approach 1 under long wave conditions, short wave conditions exhibit large motion in front arrays introducing that large wave impacts of vertical motions may reduce the structural service life and gain probability of fatigue. Among these findings, the breakwater type of protection equipment is suggested to be equipped for the FPV.

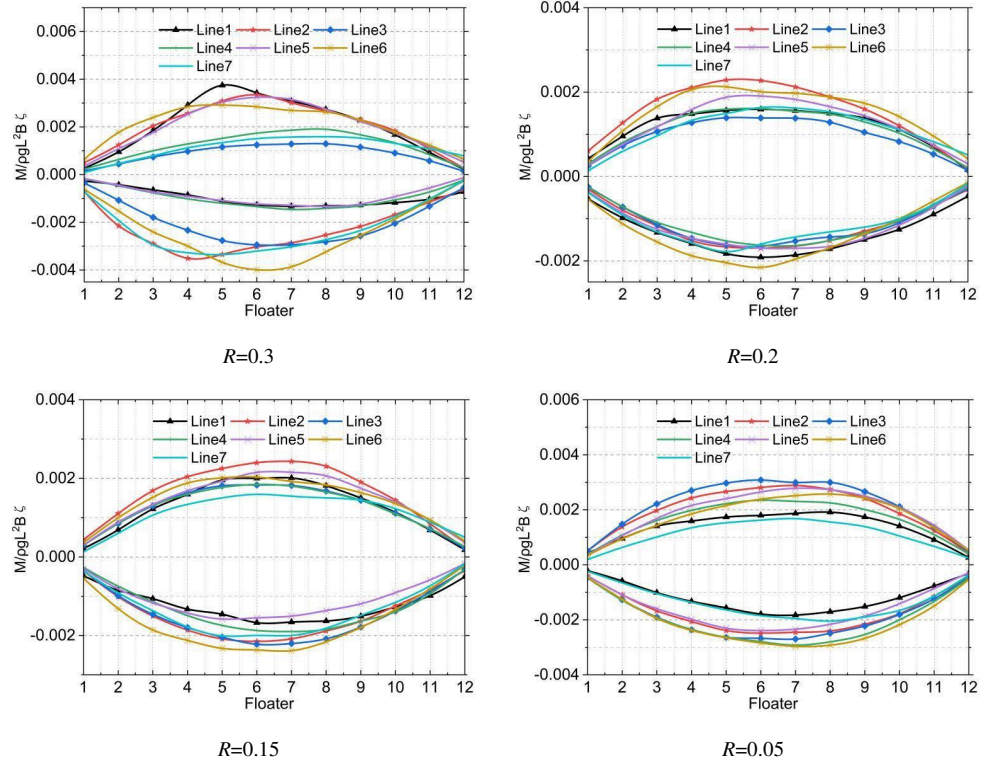


Figure 8. R_z bending moment of the hinge. Each line corresponds to each row of floaters.

The results illustrated in Figure 8 suggest that the hinge bending moment patterns across all rows generally follow a similar trend, although the magnitude varies. Interestingly, there is an asymmetry between the hogging and sagging curves, indicating potential non-linearities in the array. In the case of shorter wave conditions ($R=0.3$), the bending moment curves are markedly more unstable, and the points of maximum hogging and sagging bending moments shift across different rows.

Under short wave conditions ($R=0.3$), the bending moment curves are highly unstable. The variability of the peaks in the hogging and sagging bending moments suggests strong wave-structure interactions. Notably, the most significant bending moments are observed at different locations depending on the row. The peak values for Line1 and Line7 occur at the fifth floater, for Line2 at the fourth, for Line3 at the seventh, for Line4 at the eighth, and for Line5 and Line6 at the sixth. This instability may be attributed to short waves, consistency with heave and pitch motions, in which chaotic loads are induced by motions, causing unpredictable interactions with the floating solar farm's structure. Furthermore, moorings at Line1 and Line7 seem to have less impact in these conditions, potentially explaining the higher bending moment values observed in these rows. The reason

may be that moorings have weaker restraining capabilities on high-frequency motions.

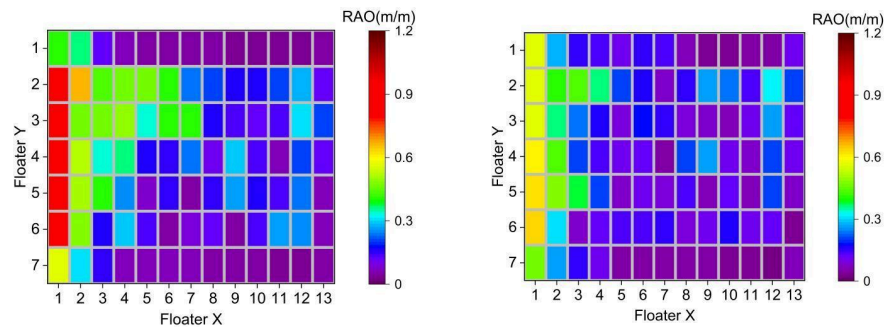
For intermediate wave conditions ($R=0.2$, $R=0.15$), there appears to be a more consistent pattern in the location of maximum hogging and sagging bending moments. For $R=0.2$, these peaks occur at Floater5 and Floater6, and for $R=0.15$, they occur at Floater6 and Floater7. This trend suggests that as the wavelength increases, the points of peak stress move progressively toward the direction of the incoming waves. The reason may be that longer waves tend to propagate more steadily through water, concentrating their pressure more towards their direction of travel resulting in the peak pressure moving towards the direction of wave propagation, wave interactions and structural responses can also have an impact.

As the wavelength continues to increase, the bending moment curves demonstrate further stabilization. The location of the peaks moves towards Floater7 and Floater8, indicating a shift in the distribution of bending stresses along the structure. In longer wave conditions, the impact of moorings appears to be more significant, contributing to reduced bending moment values in Line1 and Line7, while the hinge bending moment values for Line2 and Line6 remain consistently high. This consistency suggests that certain rows experience more pronounced stresses, potentially due to structural factors or their relative position in the array.

Despite the observed stabilization, there are noteworthy trends in the total hinge bending moment values across different rows as the wave conditions change. Beyond the shortest wave condition ($R=0.3$), increasing wavelengths ($R=0.2$ to $R=0.05$) correspond to a general increase in total bending moments for Line 3, Line 4, and Line 5. Additionally, it's worth highlighting that the highest bending moment values are observed during both the shortest and longest wave conditions, suggesting a complex interplay between wave characteristics and structural responses.

4.2 Oblique wave conditions without breakwater

From the numerical results above, it can be observed that the motion response tends to calm with the increase of wavelength, therefore the shortest wave condition which represents the most severe case is used to investigate oblique wave with four directions ranging from 15° to 60° are considered.



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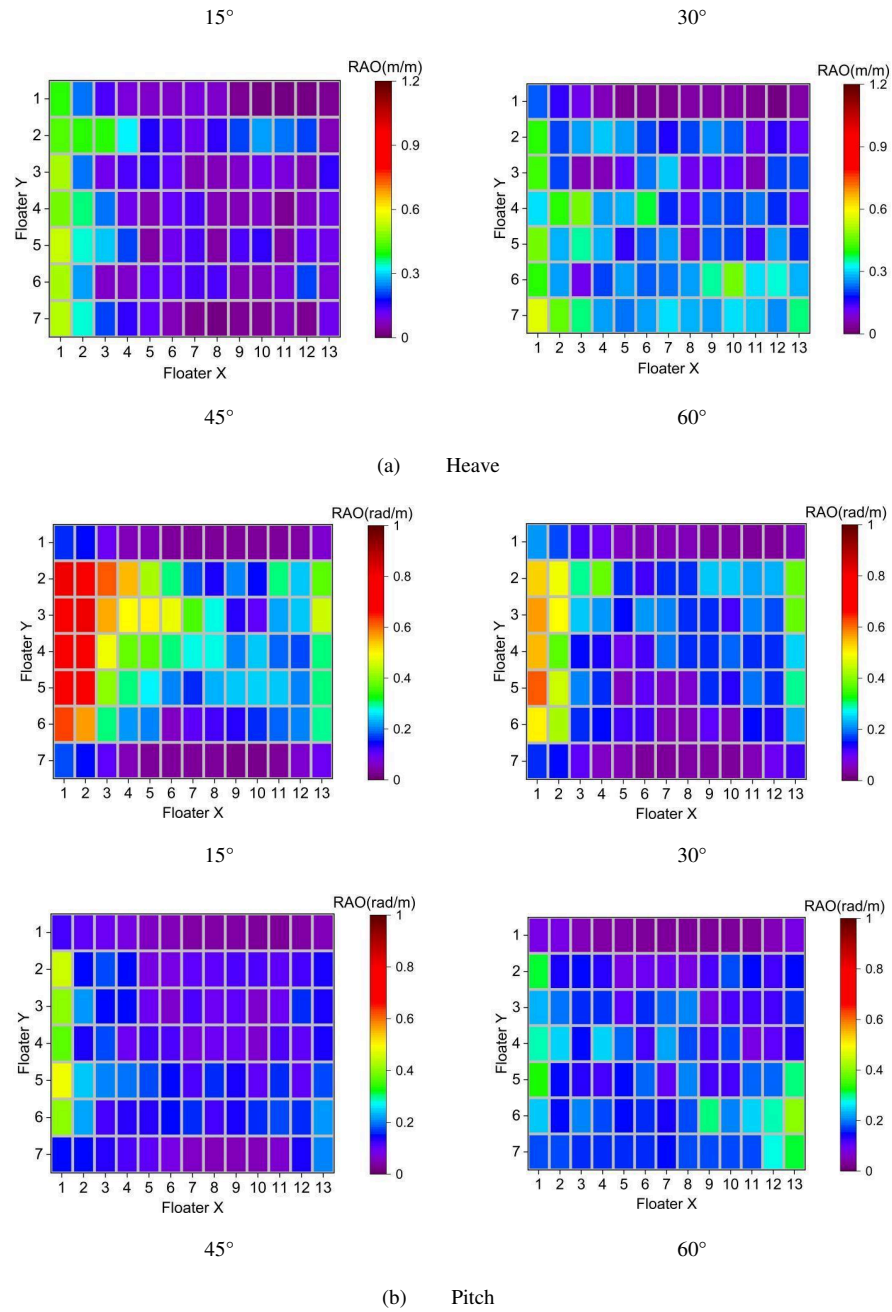


Figure 10. Heave and pitch response of modular array structure under oblique wave condition.

Figure 9a demonstrates that under a 15° wave condition, the heave response for the structures in the first column (c1) is still relatively high, albeit slightly reduced compared to the heading wave conditions. This reduction may be due to the oblique wave angle, which diffuses some of the wave energy across the structure, reducing the overall impact on the first column. In the middle region of the array, an asymmetrical undulation pattern is observed, with the heave response concentrating towards the upper part (rows 2 and 3). This asymmetry could be attributed to the oblique wave direction, which creates uneven wave pressures and dynamic interactions with the structure. As the direction angle increases, the heave response for the structures in the first column decreases. The undulation in the middle region also diminishes notably under 30° and 45° wave directions, suggesting that these angles lead to a more distributed impact across the array, reducing the intensity of wave-structure interactions. Under the 60° wave condition, the heave response exhibits a clear decreasing trend from row 7 inwards. This pattern indicates that waves approaching at a steeper angle (60°) have less impact on the inner rows, likely due to the increased dispersion of wave energy and reduced direct contact with the waves. The pitch response, shown in Figure 9b, follows a similar trend to the heave response. The patterns of pitch response are consistent with those observed in heave, reinforcing the notion that the angle of the incoming waves significantly influences the structural behaviour. The pitch response also indicates that mooring methods and structural connections play a critical role in stabilizing the structure against oblique wave forces. The mooring angle is set at 45° , which is a crucial factor in reducing the structural motion response. Under 45° wave conditions, the structural motion response is relatively small, indicating that this angle provides a balanced distribution of wave forces and minimizes dynamic stress on the structure. This finding could have significant implications for the design and optimization of mooring modules in floating solar farms, suggesting that a careful selection of mooring angles and connection methods can improve stability and reduce mechanical stress.

The analysis of oblique wave conditions reveals that the angle of the wave approach significantly affects the motion response of floaters in a floating solar farm. Understanding these effects is crucial for the design and optimization of these structures to ensure they can withstand various wave conditions while maintaining stability and structural integrity.

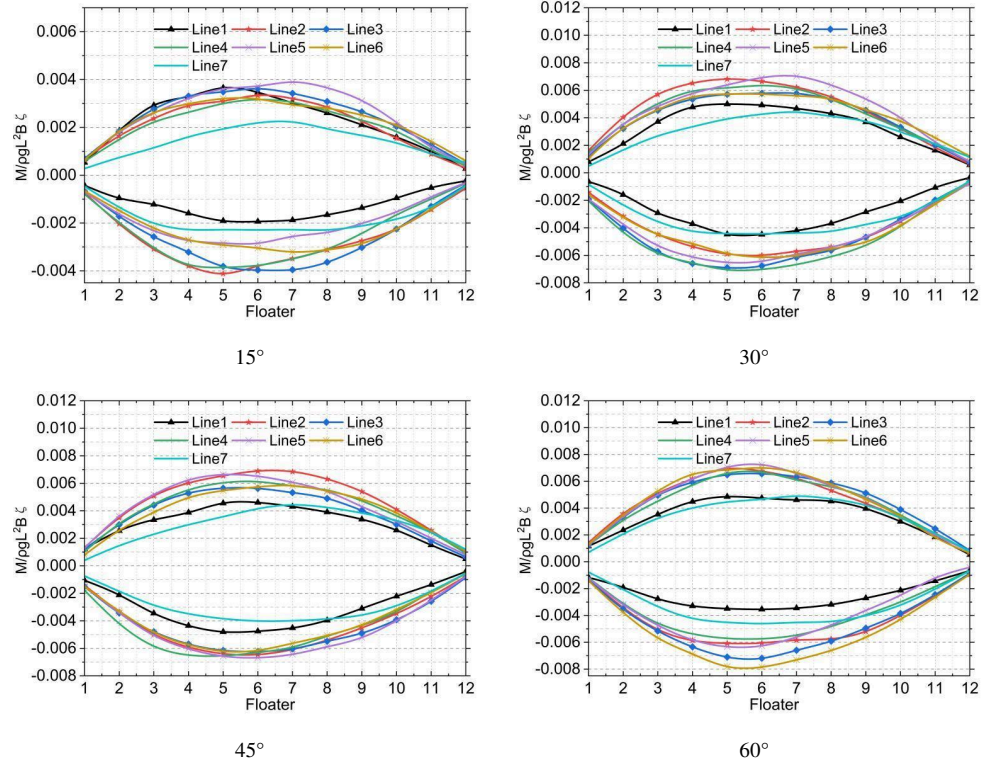


Figure 10. R_z bending moment of hinge under oblique wave condition.

Figure 10 illustrates the variation in hinge bending moment values within the floating solar farm array under oblique wave conditions. The results show a significant increase in bending moment under these conditions, with notable variations depending on the row and wave direction. The hinge bending moment values increase across the array, indicating that the structure experiences greater mechanical stress when waves approach from different angles. Despite this overall increase, the bending moment values for Line1 and Line7, which are connected to the moorings, remain at the lowest levels. This observation suggests that the moorings play a critical role in stabilizing the structure and reducing bending stress at the outer edges of the array. Under 30° and 45° wave conditions, the bending moment curves for Lines 2 through 6 exhibit relatively small differences between hogging and sagging. This uniformity may indicate that the wave forces are more evenly distributed across these rows when the wave angle is moderate, leading to a balanced structural response. However, the bending moment curves for these lines vary significantly under 15° and 60° wave conditions. In these cases, the sagging curve amplitudes show greater variability, suggesting that the structural response is more sensitive to changes in wave angle. This variability might be related to the arrangement angles of the moorings, which could influence how the structure responds to oblique waves. At 15° and 60° wave conditions, the structure may

experience asymmetric forces due to the mooring arrangement, leading to uneven distribution of stress and increased bending moment in certain areas. This finding highlights the importance of carefully designing mooring modules to ensure an even distribution of wave forces, particularly under oblique wave conditions.

4.3 Heading wave conditions with breakwater

Based on the numerical simulation results above, it is evident that there is significant motion response in the front region. Therefore, a breakwater is designed at the front of the array, with specific parameters shown in Figure 11. The breakwater is completely fixed, and it is positioned at 0.8 m from the array. The breakwater is modeled as a fixed structure to provide better wave attenuation, which is crucial for protecting the FPV system. A moving floating breakwater could allow more wave energy to pass through and reach the FPV array. Fixed breakwaters are commonly in contemporarily evolving FPV designs used and have been shown to offer reliable protection, as demonstrated in previous studies like Zanden et al. [56] and Panjwani et al. [57]. Its length is 12.4 m and its draught is 0.2 m. Following that, the same numerical simulation is carried out with this breakwater design, resulting in additional findings.

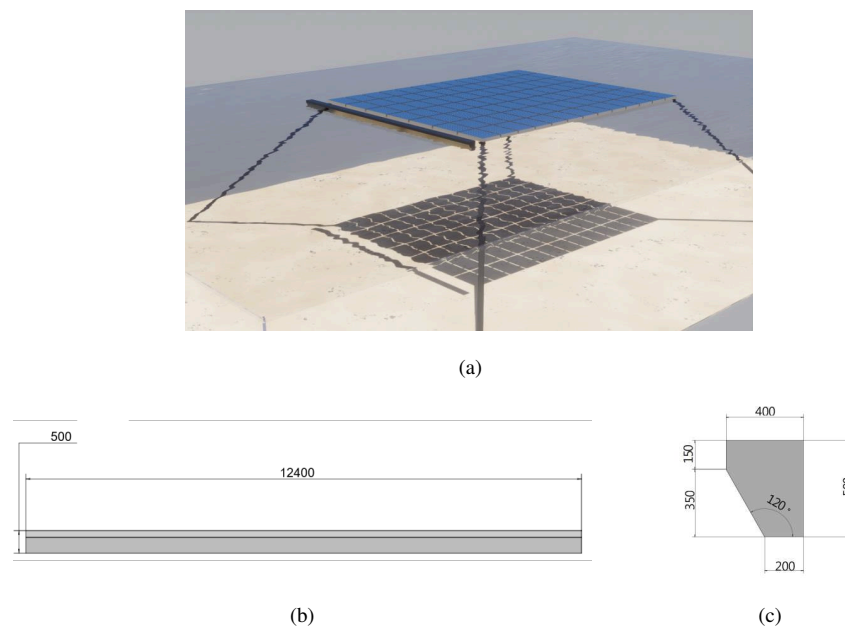


Figure 11. The optimized numerical model of FPV system. (a) overview diagram of the system, (b) front view of the breakwater, (c) side view of the breakwater. Unit: mm.

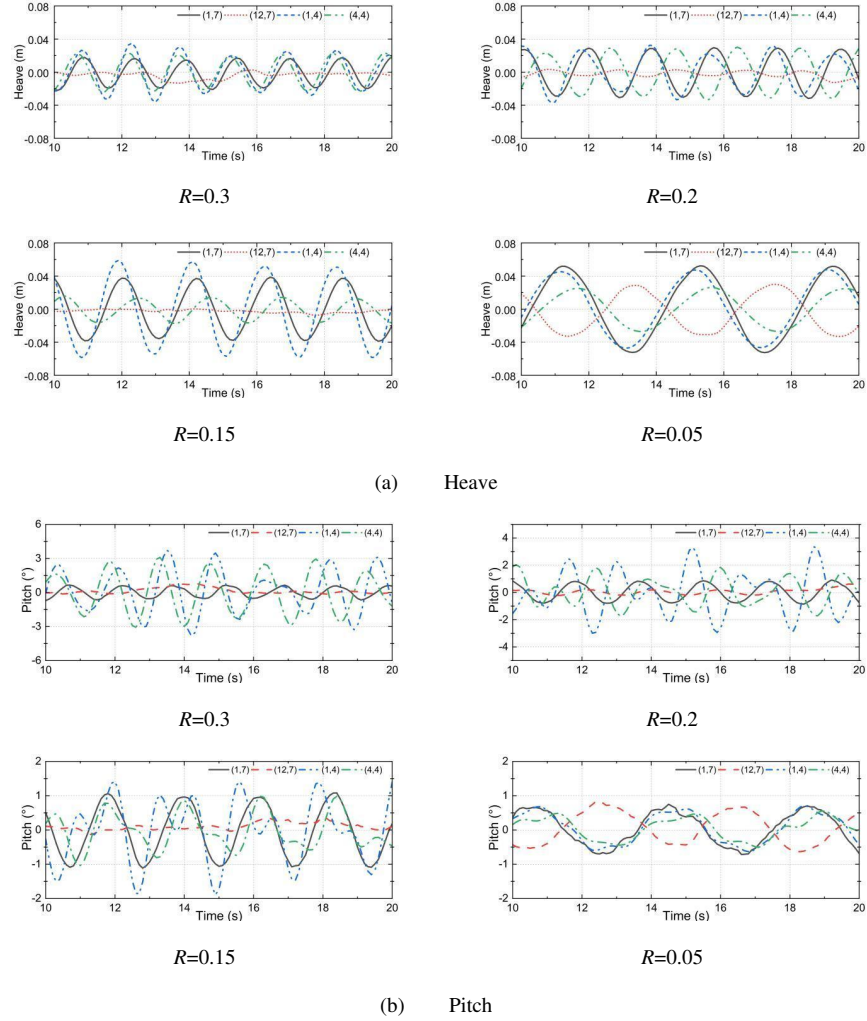


Figure 12. Mechanical response curves of floaters at different positions in the array with breakwater.

Based on the time domain curves in Figure 12, the addition of a breakwater appears to influence the heave and pitch responses of floaters at various positions within the array. The observed effects vary depending on the wave ratio R , representing the relationship between structure length and wavelength, with notable differences across the different floaters and wave conditions.

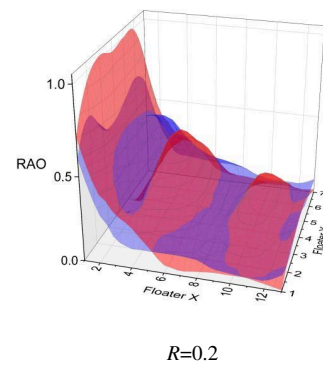
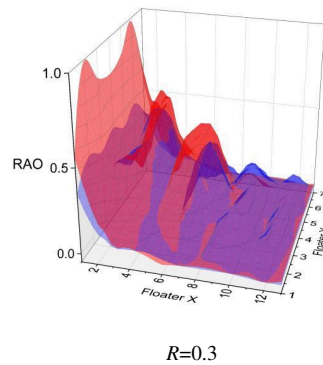
For $R=0.3$, the heave response for floaters (1,7), (1,4), and (4,4) notably decreases with the addition of the breakwater. This suggests that the breakwater effectively reduces the impact of shorter waves, mitigating the

upward force and vertical movement. However, for the floater (12,7), the change in heave response is minimal, indicating that the breakwater's effect is less pronounced at the tail end of the array. The pitch response increases for floaters (4,4) and (1,4), indicating that the breakwater might influence the rotational movement of these floaters. The pitch response for floaters at positions (1,7) and (12,7) shows no significant change, suggesting that the breakwater's impact on these outer floaters is minimal.

For $R=0.2$, the heave response of the floater (1,4) decreases, while that of the floater (4,4) increases. This contrasting behavior may be due to the interaction between the breakwater and the wave energy distribution. The heave response for floaters (1,7) and (12,7) decreases slightly, indicating a moderate reduction in vertical movement for these rows. The pitch response increases for floaters (4,4), (1,4), and (1,7). This trend indicates that the breakwater can induce rotational effects depending on the floater's position in the array. The floater (12,7) shows no change in pitch response.

For $R=0.15$, there is a slight decrease in heave response for floaters (1,7) and (1,4), while the floater (4,4) shows an increase in heave response. This shift in pattern suggests that the breakwater's influence on heave varies with the wave ratio and the floater's position. The heave response for the floater (12,7) shows minimal change. The pitch response increases for the floater (1,4), but there is no significant change for the other floaters.

For $R=0.05$, the responses of all four floating bodies remain essentially unchanged, indicating that the breakwater has little impact on vertical and rotational movement under longer wave conditions. The addition of a breakwater affects the heave and pitch responses of floaters in different ways, depending on the wave ratio and the position within the array. While shorter wave conditions tend to show more pronounced effects, with changes in both heave and pitch responses, longer wave conditions reveal minimal impact.



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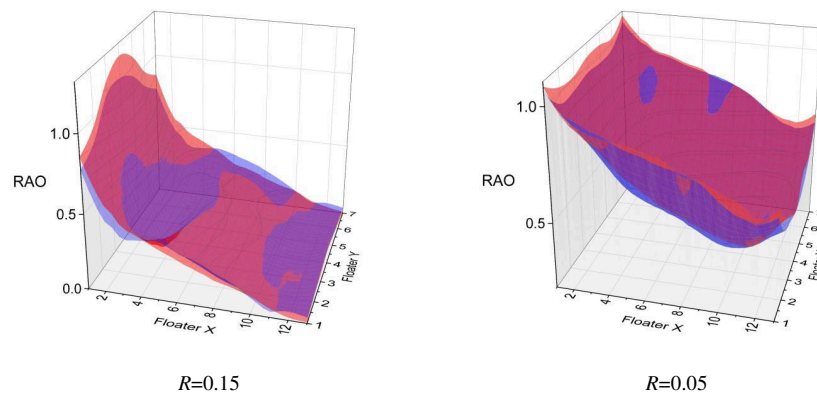


Figure 13(a). Comparison of heave response with and without breakwater under 0° wave direction. The blue surface represents the situation with breakwater.

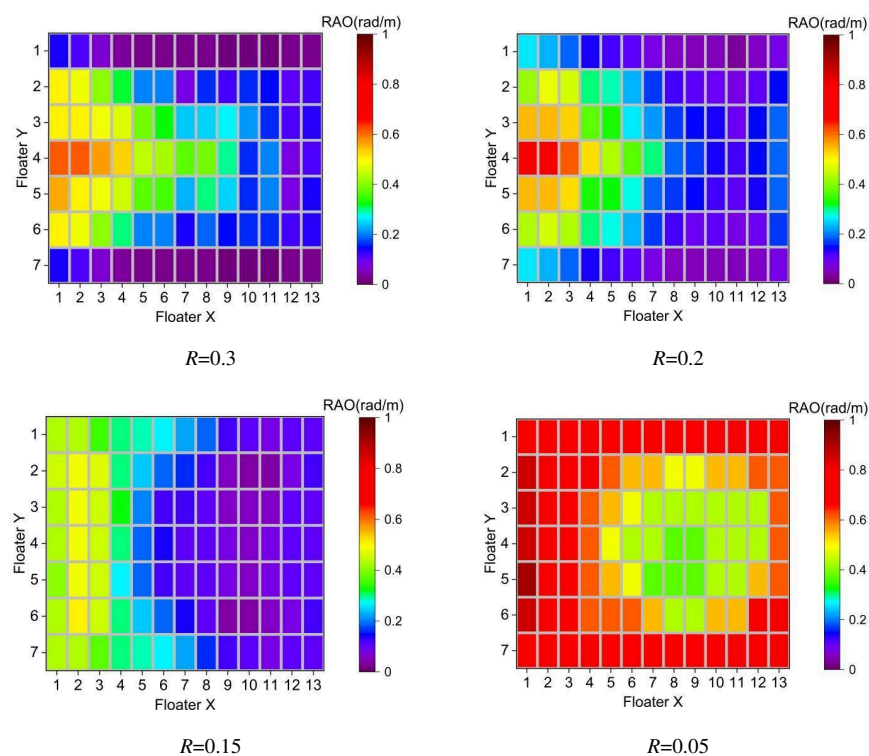
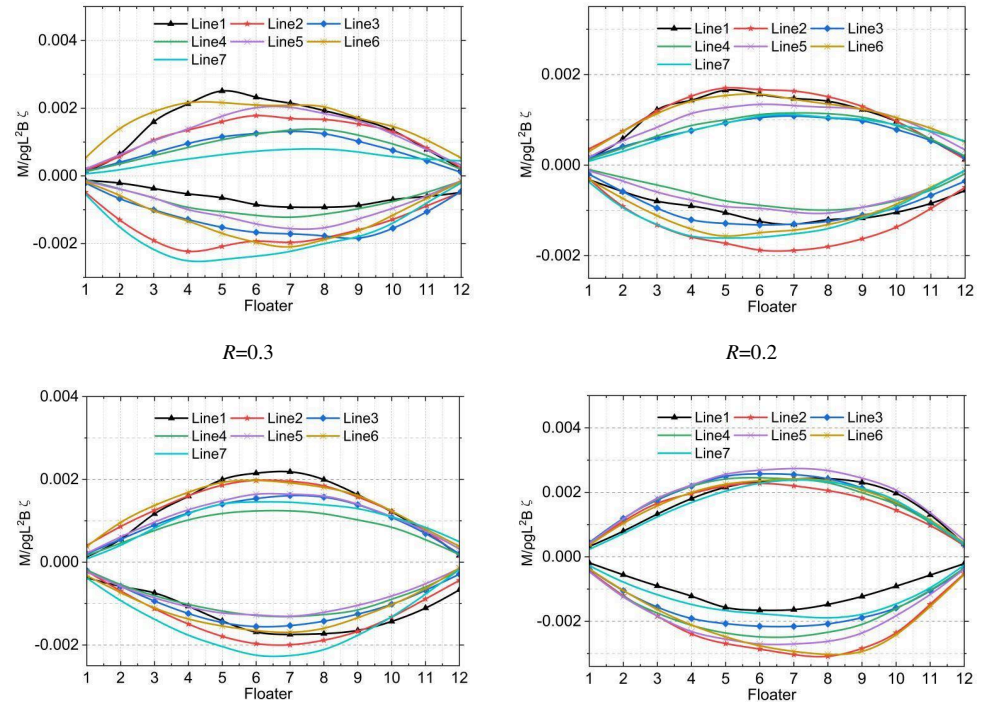


Figure 13(b). Pitch

Figure 13. Heave and pitch response of the modular array structure with breakwater.

In Figure 13a, the blue surface represents the situation with the breakwater, the data indicate that the breakwater's effect on heave response is most notable under shorter wave conditions. The reduction in heave response can be attributed to the breakwater's ability to attenuate wave energy before it reaches the floating solar farm, thus diminishing the vertical movement of the floaters in the front region. This reduction can be as high as 56%, demonstrating the breakwater's effectiveness in controlling heave-related stress. However, as wave conditions transition to longer wavelengths, the reduction in heave response becomes less pronounced. This change suggests that longer waves retain more energy and are less affected by the breakwater, thereby exerting more force on the floaters. Figure 13b shows the pitch response with and without the breakwater. The general pattern of pitch response mirrors that of heave response, with a significant reduction in the front of the array when the breakwater is present. This reduction can also be attributed to the breakwater's role in mitigating wave energy and thus reducing the rotational forces acting on the floaters. A notable exception is observed for the floater in the fourth row in the front region when $R=0.2$. In this case, the pitch response increases despite the presence of the breakwater. This anomaly could be due to specific interactions between the breakwater and wave energy distribution, causing unexpected rotational forces in certain areas.



$R=0.15$

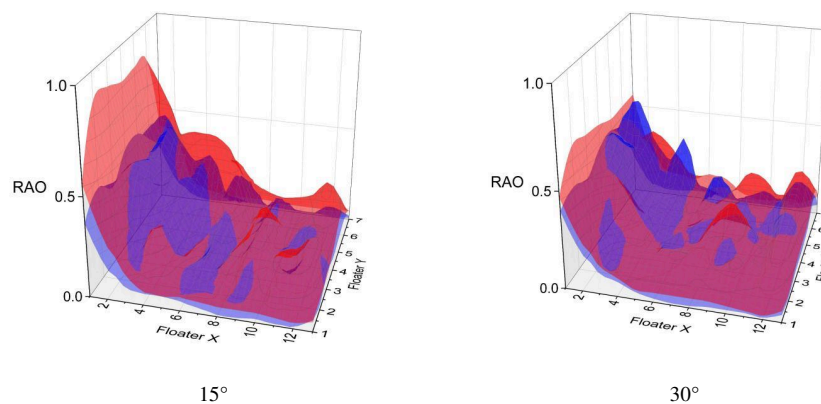
$R=0.05$

Figure 14. R_z bending moment of hinge with breakwater.

In Fig.14, the impact of the breakwater on the array's hinge bending moments is significant. At $R=0.3$, the average bending moments for Line1, Line2, Line6, and Line7 are reduced by about 35%, while those in the central portion, Lines3, Line4, and Line5, decrease by a smaller margin of about 20%. At $R=0.2$, the average bending moments for the outer four rows are reduced by about 16%, while those for Line 3, Line 4, and Line 5 decrease by about 28%, potentially due to altered wave dynamics and energy distribution within the array. When R is 0.15, the outer four rows' average bending moments decrease by 9%, and the central three rows reduce by 25%, this trend implies that longer waves tend to retain more energy, requiring additional dampening in the central regions. At $R=0.05$, the bending moment for Line7 increases by about 20%, Line5 increases by about 11%, Line3 decreases by about 18%, while the other rows exhibit little change, resulting in almost no overall change in hinge moments. The increase in bending moments in some rows might indicate that the breakwater's effectiveness diminishes with longer wavelengths, possibly due to its limited capability to fully dampen wave energy. This indicates that as the wavelength increases, the impact of the breakwater varies, leading to mixed results in bending moments.

4.4 Oblique wave conditions with breakwater

Similarly, simulations are conducted for the wave conditions in Section 4.2 to study the effectiveness of this breakwater under oblique wave conditions.



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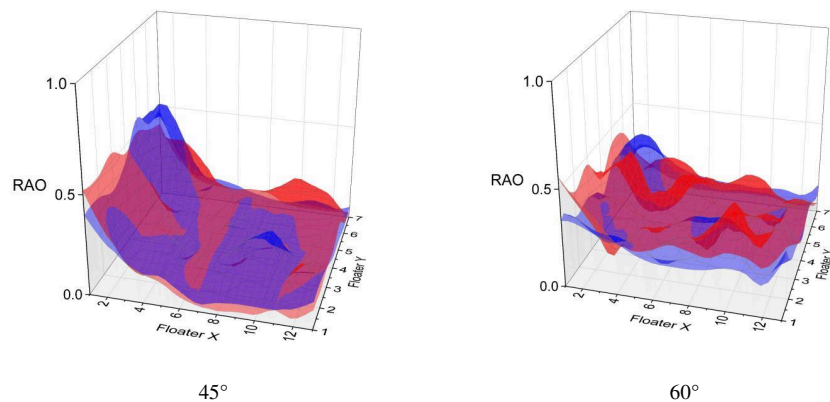
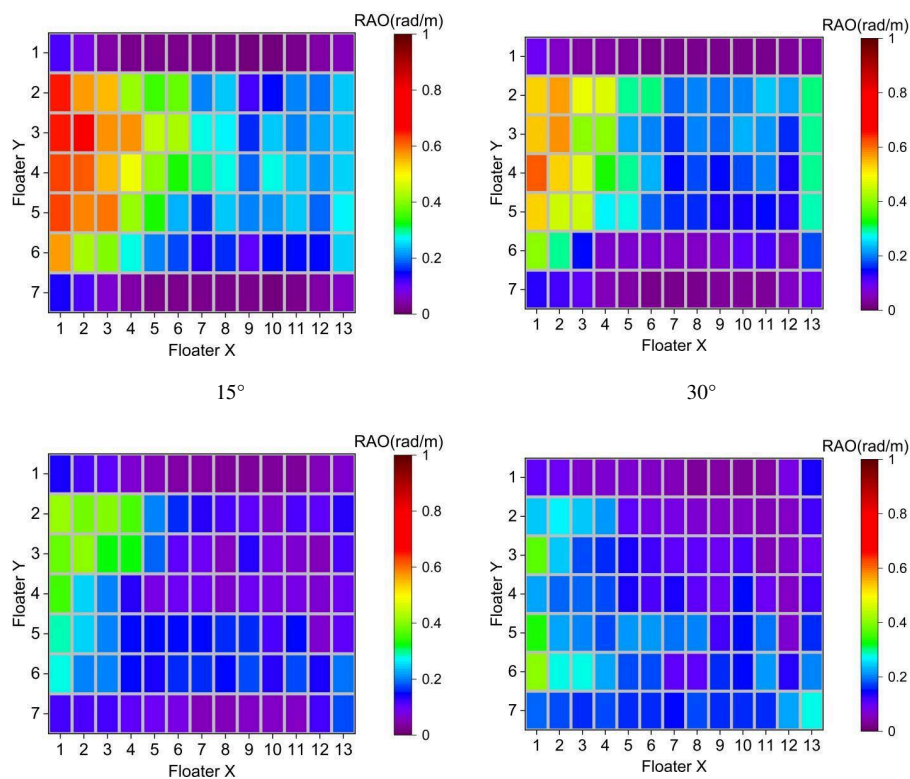


Figure 15(a). Comparison of heave response with and without breakwater under oblique wave conditions.
The blue surface represents the situation with breakwater.



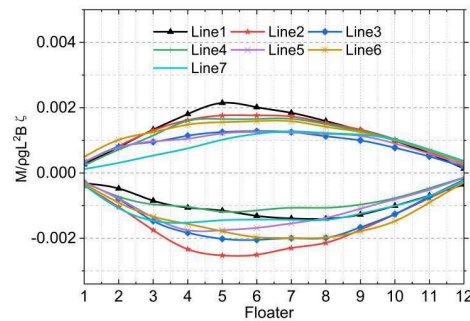
45°

60°

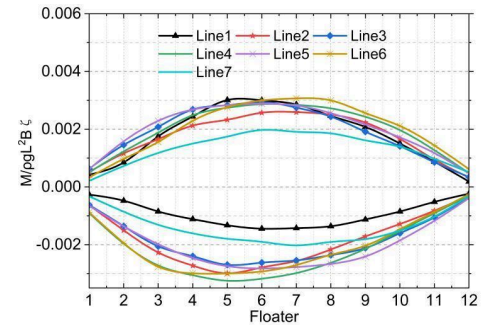
Figure 15(b). Pitch

Figure 15. Heave and pitch response of modular array structure with breakwater under oblique wave condition.

Figure 15a illustrates the significant impact of the breakwater on the heave response of the structures in the first column under oblique wave conditions. This reduction is most pronounced at lower wave angles, suggesting that the breakwater effectively dampens wave energy when waves strike the array at shallower angles. This effect diminishes as the wave angle increases, indicating that oblique waves may bypass or lose some of their energy-mitigating effects due to the breakwater's geometry. However, there are occasional instances where the heave response increases for certain floaters. This anomaly could be due to the wave's interaction with the breakwater, creating unexpected turbulence or wave refraction that leads to localized increases in vertical motion. Under the 60° wave condition, the variation in the lower part of the array is minimal, indicating that the breakwater's impact is less effective at higher wave angles. Given these results, additional breakwaters could be strategically placed throughout the array to address areas with increased heave response. This approach might help optimize the overall performance of the array and maintain a more consistent reduction in heave across different wave angles. Figure 15b shows that the pitch response follows a similar trend to the heave response. The breakwater's presence generally reduces the pitch response in the forward area of the array, with a decrease of approximately 15%.



15°



30°

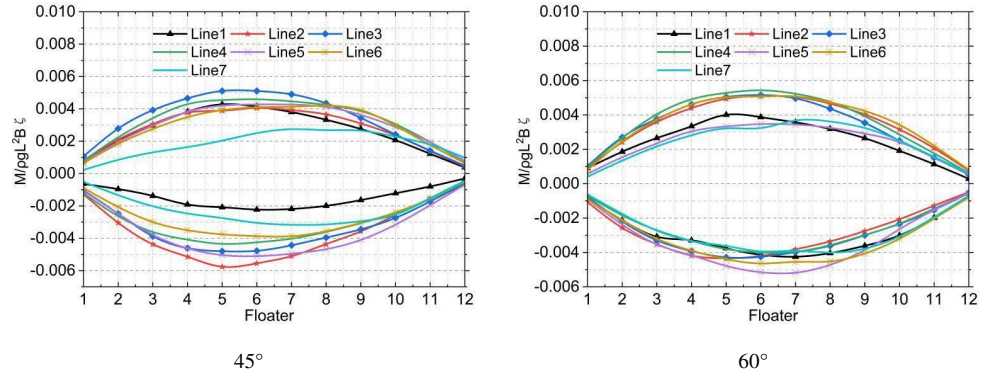


Figure 16. R_z bending moment of hinge under oblique wave condition with breakwater.

Comparing Fig.10 and Fig.16, under short-wave conditions ($R=0.3$), the degree of impact that the breakwater has on the array varies with different wave directions. When the wave direction is 15° , the presence of the breakwater reduces the average hinge bending moment values by about 45%. At 30° , the reduction in bending moments is even more pronounced, with an average decrease of about 55%. This greater reduction suggests that the breakwater's design is particularly effective at suppressing short-wave energy at this angle. It could be due to optimal wave refraction or dispersion, leading to reduced stress on the array. At 45° , it's about 28%; and at 60° , the decrease is around 23%. This lower reduction rate indicates that the breakwater's effect diminishes as the wave angle increases. This reduced suppression could be due to the oblique wave direction allowing more wave energy to bypass or interact differently with the breakwater, resulting in less effective dampening.

Since the breakwater designed in this study is only arranged in one direction and its wave attenuation performance in oblique waves can still be further improved by increasing its width or encircling the front part. However, it is worth noting that the wave direction in coastal regions will be mostly heading, which is the most relevant case for the studied FPV model. For offshore applications, 360° design of the breakwater is recommended.

4.5 Sensitivity study on the breakwater's dimensions

To study the wave-dissipating capability of the breakwater with different dimensions, the effects of varying the height and width of the breakwater were tested. Following a control-parameter approach, each test only changed either the height or the width based on the initial design. The mean heave response amplitude of the first row of floating structures was chosen for data analysis here.

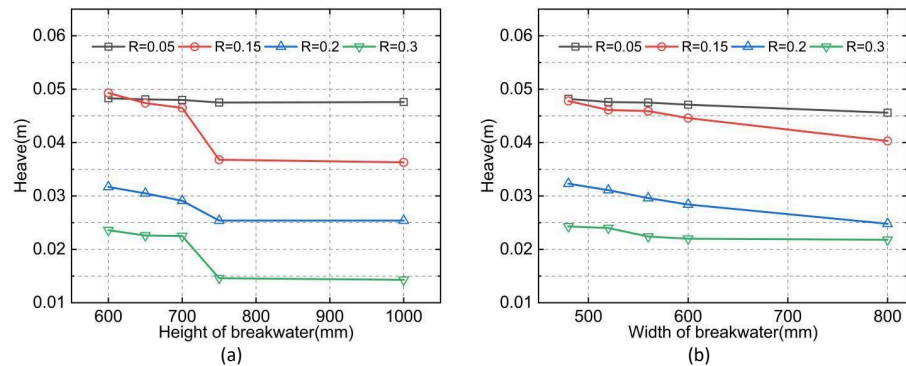


Figure 17. Heave response of the first row of FPV behind different sizes of breakwater.

Breakwater dimensions are considered on a range of height and width: from 600 mm to 1000 mm, 480 mm to 800 mm. 40 relevant cases have been conducted with the wave conditions from $R = 0.05$ to 0.3 . Figure 17 reveals that increasing the size of the breakwater leads to a corresponding decrease in the heave response of the first row of structures. When the height of the breakwater is increased, the draught depth also increases, leading to the most significant reduction in heave. However, when the height increases to more than 800 mm, the reduction in heave response is minimal, as the curve tends to converge, indicating that the additional wave-dissipating benefit from increasing the breakwater's height is limited. As the width of the breakwater increases, the relative structural length to wavelength increases, and the enhancement for the wave-blocking performance can be seen. This suggests that wider breakwaters should be used to tackle longer waves. In practical design, both the height and width dimensions of the breakwater can be designed accordingly to the dominating site condition to achieve the optimal wave-dissipating effect. Further studies could explore other aspects of breakwater design, such as irregular shapes, to determine additional factors that contribute to the effectiveness of breakwater structures in various wave conditions.

5. Conclusions

To support the deployment of FPV systems in seas, this paper presented simulations of a hinged modular floating solar array in waves, focusing on the influence of an upstream breakwater. Through systematic cases in various heading and oblique waves in combination with and without a breakwater, the motion characteristics and joint loadings of the array were analyzed. The conclusions drawn from the study are as follows:

- The motions of the modular FPV system significantly varies with wave conditions, while this can be predictable by mathematically relating each degree of freedom with λ and β .
- In heading wave conditions, FPV motions agree with known wave energy dissipation theories; longer waves induce the most significant vertical motion amplitudes and a substantial reduction in motion is evident along the wave propagation direction.
- In heading waves, the triangular-shaped breakwater effectively reduces the FPV motions by up to 56% and the loading on joints by up to 35%, most effective in short wave conditions. In longer wave conditions, the breakwater was less effective, and some joints can have increased loading than the case without breakwater. In addition, the increase in size enhances breakwater's ability to reduce array motion response.
- In oblique waves, the breakwater can reduce the FPV motions by approximately 15%, and this does not cover the area that is not shaded by the breakwater. Despite that the breakwater effect on motions is not significant in oblique waves, the loading on joints can still be decreased by up to 55%, which can attribute to wave diffractions.

Future research can simulate realistic sea conditions, considering the holistic wave-blocking performance of the breakwater in real-site wave spectrums [58]. The mooring method and design for the shapes of breakwaters may be optimised through advanced machine learning algorithms [59][60]. Moreover, FPV's mooring lines' connection locations and physical properties will be interesting to investigate [61]. It is recommended to incorporate tidal variations and their effects on mooring line tensions into our simulations to further refine and validate our model. More advanced finite element analysis (FEA) software can be used to perform more comprehensive simulations and analyses in future work, such as detecting collisions between FPVs. In addition, it is recommended to investigate the integration of porous medium flow models to better represent wave energy dissipation in floating breakwater systems [62], as well as the consideration of wind loads and their coupling effects with waves on floating structures [63][64].

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Data Availability

All data underlying the results are available as part of the article and no additional source data are required.

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Effects of a breakwater on a floating solar farm in heading and oblique waves

Zou, Detai; Wei, Yujia; Ou, Binjian; Zhang, Chao; Chu, Shengnan ...

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