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Geometric asymmetry in the energy conversion and wave attenuation of a powertake-off-integrated floating breakwater

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17 Abstract

A hybrid system integrating a power take-off (PTO) system into a floating breakwater is a 18 promising candidate for both shoreline protection and commercial wave energy extraction. 19 Although geometric asymmetry is important to such PTO-integrated breakwaters, its role in 20 energy conversion efficiency and wave attenuation is poorly understood. In this study, a two-21 22 dimensional semi-analytical model dealing with floats with arbitrary bottom shapes is 23 established based on the potential flow theory. To quantify the geometric asymmetry reflected 24 by PTO-integrated breakwaters with different contours, the degree of asymmetry and the absolute asymmetry are newly defined mathematically. A set of symmetric and asymmetric 25 PTO-integrated breakwaters are comparatively studied to demonstrate the effect of linear PTO 26 damping and geometric asymmetry on the transmission coefficient, the reflection coefficient, 27 and the energy conversion efficiency. Results show that no matter the hybrid system is 28 29 symmetric or asymmetric, a larger PTO damping is beneficial for wave attenuation in longer 30 waves, particularly at the heaving natural period of the device. On the premise that the PTO damping is optimized, an increase in the degree of asymmetry greatly improves the energy 31 conversion efficiency. An increase in the absolute asymmetry slightly improves wave 32 33 attenuation.

Keyword: Breakwater; Wave energy converter; Hybrid system; Geometric asymmetry; Energy
 conversion efficiency; Wave attenuation

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1 **1. Introduction**

2 The extensive and commercial exploitation of wave energy is hindered by the high 3 manufacturing and installation cost of WECs. A practical solution is to incorporate WECs in 4 available oceanic or coastal infrastructures to form an integrated system [1]-[5], wherein the 5 infrastructures provide an installation foundation for the WECs. The integration of WECs and breakwaters is beneficial from their cost-sharing and compatible functions of energy extraction 6 and shoreline protection. Due to the variety of WECs [6] and breakwaters [7], the layout of a 7 8 hybrid system is quite diverse [8]-[10]. Two methods are usually adopted while incorporating 9 an oscillating body WEC: 1) the WEC is deployed as a separated unit on the seaward side of the breakwater, such as in Zhang et al. [11], Reabroy et al. [12], and Zhang et al. [13]. 2) the 10 floating breakwater is used as the oscillating component and the power take-off (PTO) system 11 is integrated in it (PTO-integrated breakwater hereafter), for instance in Zhang et al. [14] and 12 13 Ning et al. [15].

14 The studies of PTO-integrated breakwaters could roughly be categorized into two aspects according to the subject. In the first, the subject is a standard rectangular float. Investigations 15 are mainly on the influence of geometric factors and generator parameters on the hydrodynamic 16 and power performance. Ning et al. [15] conducted experiment on a wave tank to study the 17 effect of incident wave conditions, PTO damping, and dimensions of the breakwater on energy 18 conversion efficiency and wave attenuation. They found that the PTO damping force and the 19 20 draft and width of the breakwater play important roles in the hydrodynamic performance. Using 21 Open-Foam, Ma et al. [16] extended the work of Ning et al. [15] to study the performance of 22 three kinds of integrated PTO and found that applying Coulomb damping is suitable for wave 23 energy capturing and coastal protection. Zhao et al. [17] took an experiment to study the 24 influence of PTO damping on the wave loads acting on different areas of the float. They found 25 that the wave pressure on the front and back walls is seriously affected, whereas the wave 26 pressure on the middle section of the bottom is the smallest and just slightly affected by the PTO damping force. 27

In the second, the subject is no longer a standard rectangular float. Either the number of floats 28 29 is increased or the cross-section of a single-float is modified as new concepts. Investigations 30 are still on the influence of different factors on the performance of the system. Using the Computational Fluid Dynamics (CFD) approach, Chen et al. [18] studied a PTO-integrated 31 32 breakwater in which a permanent magnet linear generator is installed inside a sealed floating 33 horizontal circular cylindrical buoy. Its maximum primary energy conversion efficiency could be close to 25% with a corresponding wave transmission coefficient ranging from 0.7 to 0.75. 34 35 Ning et al. [19] extended their work in Ning et al. [15] and proposed a dual float design. They studied the influence of the geometric parameters of the system and found that the heaving 36 natural frequency and the spacing between the two floats are critical factors to its performance. 37 38 The bandwidth of energy conversion in the frequency domain is also broader compared with a 39 single float. Guo et al. [20] further extended the work and proposed a triple float design that can absorb wave energy from both heave and pitch motions. They studied the influence of the 40 width and draft of the floats and the spacing between the floats and found that the effective 41 42 energy conversion bandwidth increases with the decrease of the width and draft of the front 43 float, and the spacing also plays an important role. Based on potential flow theory with viscous correction in the frequency domain, Zhang et al. [21] design and optimize a three-dimensional 44

1 floating breakwater integrated with a WEC array, and find that the WECs perform better when

it is placed in the wave focusing areas, which appear more frequently close to the breakwater.
The vertical forces on the breakwater significantly increase and the horizontal forces are

4 decreased.

5 Since Mei [22] indicated that the efficiency of a symmetric WEC could not exceed 50%, 6 some subsequent concepts using an asymmetric float instead of a symmetric float have been 7 proposed and studied. Perhaps the first such device being propounded is the "Berkeley Wedge". 8 Based on the idea that the WEC should 1) be highly asymmetric to overcome the efficiency limit of 50% and 2) minimize the impediment of viscosity, the odd shape of Berkeley Wedge 9 was obtained. The Berkeley Wedge WEC was later used as a PTO-integrated breakwater [23]. 10 11 Zhang et al. [14] studied the energy conversion efficiency and wave attenuation of three 12 asymmetric PTO-integrated breakwaters with different bottom configurations and found that a 13 simple triangle-baffle model is as efficient as the Berkeley Wedge. The efficiency could be up to 93%. Chen et al. [24] used a Particle in Cell (PIC) numerical scheme to optimize the cross-14 15 section of a PTO-integrated breakwater for more energy absorption and less wave transmission at the same time. They found that using a small circular arc corner instead of a rectangular 16 17 corner on the seaward side greatly improves the energy conversion efficiency with a slight 18 decline in wave attenuation.

19 From the literature, it is consensual that asymmetry has a significant influence on the energy 20 conversion efficiency and wave attenuation of a PTO-integrated breakwater. Although previous research has taken efforts in optimizing the standard rectangular float or proposing new designs 21 based on this idea, the way the performance is influenced by asymmetry and corresponding 22 mechanisms are somewhat overlooked. To fill this gap, a theoretical investigation was 23 24 performed. The novelties of this study are as follows: 1) to propose and validate a semi-25 analytical approach based on the eigenfunction expansion method dealing with floats with arbitrary bottom shapes; 2) to introduce the concepts of the degree of asymmetry and the 26 27 absolute asymmetry and establish criteria for qualifying and comparing such property between 28 different PTO-integrated breakwaters; 3) to investigate the role of asymmetry in the 29 proportional distribution of attenuated, reflected, and absorbed wave energy; 4) to study the 30 effect of three approaches that can modify the asymmetry of a triangular-wedge PTO-integrated 31 breakwater on its energy conversion efficiency and wave attenuation, providing a useful 32 reference for practical design and application.

33 The rest of the paper is structured as follows. In Section 2, the mathematical model describing 34 interactions between waves and a PTO-integrated breakwater with arbitrary bottom shape is 35 given. Only the major steps are displayed in this part whereas the detailed expressions of some 36 terms are given in the Appendices for readers to capture the essence conveniently. In Section 3, convergence tests on bottom shape asymptote are conducted, and a comparison of results with 37 a widely used numerical schematic is performed to validate the present model. A comparative 38 study using a wide range of PTO damping on three symmetric and asymmetric PTO-integrated 39 40 breakwaters is done to check if installing a PTO system could improve its wave attenuation. 41 The role of geometric asymmetry in energy conversion efficiency and wave attenuation is 42 investigated in detail. In Section 4, three approaches to change the geometric asymmetry of a 43 triangular-wedge PTO-integrated breakwater are examined. Their influence on the performance 44 of the breakwater is investigated. In Section 5, conclusions are drawn.

3

1 **2. Mathematical model**

2 2.1. System description and definition of degree of asymmetry

A two-dimensional (2D) PTO-integrated breakwater with two vertical sidewalls and an 3 arbitrary bottom shape is shown in Figure 1. The breakwater is allowed for heave motion only 4 5 and moorings are not used, as in Refs [11][14]. The PTO is idealized as a linear damping with 6 one end connecting to the breakwater and the other connecting to the seabed. Wave power is 7 generated by the heave motion of the breakwater [11][14]. A global Cartesian coordinate system oxz is adopted with its origin being the intersection of the still-water surface and the float's 8 vertical central line while the system is in equilibrium. The water has a finite depth of h. The 9 immersed part of the float is bounded by two vertical sidewalls at $x = \pm w^{B}/2$ and an 10 arbitrary bottom z = -d(x) for $|x| \le w^{B}/2$. 11

12 To adopt the semi-analytical approach, the original bottom is approximated by discretizing 13 it into a number (N) of steps. The *i*th step begins from $x = x_{i-1}$ to $x = x_i$ with a draft $d_i =$ 14 $d([x_{i-1} + x_i]/2), i = 1, ..., N$. Note that $x_0 = -w^B/2$ and $x_N = w^B/2$, and let $d_0 =$ 15 $d_{N+1} = 0$. Due to the presence of the asymptotic float, the fluid domain is divided into N + 216 columns: Ω_0 for $x < x_0$ and $-h < z < -d_0$; Ω_i for $x_{i-1} < x < x_i$ and $-h < z < -d_i$, 17 i = 1, ..., N; Ω_{N+1} for $x > x_N$ and $-h < z < -d_{N+1}$.

18





Figure 1 A diagram of the 2D PTO-integrated breakwater

The aim of the present paper is to investigate the effect of geometric asymmetry in the energy 21 22 conversion and wave attenuation of a power-take-off-integrated breakwater, therefore the 23 concepts of the degree of asymmetry (DoA) and the absolute asymmetry are introduced to characterize its geometric asymmetry. Note that in these concepts, the bottom shape is assumed 24 25 as gentle and continuous curves without sharp turnings. As shown in Figure 1, the displacement 26 of the PTO-integrated breakwater is divided into three parts: the upper symmetric part with a 27 displacement of V_S and a draft of d_S , the asymmetric part with a displacement of V_A and a total draft of d_A , which is the sum of the part on the seaward side of the central line with a 28 displacement of V_A^{sea} and the part on the lee side of the central line with a displacement of 29 $V_{\rm A}^{\rm lee}$. The DoA of the PTO-integrated breakwater is defined as 30

$$\gamma = \gamma_1 \cdot \gamma_2, \tag{1}$$

1 $\gamma_1 = d_A/w^B$ (2)

$$\gamma_2 = \left(V_A^{\text{lee}} - V_A^{\text{sea}}\right) / \left(V_A^{\text{lee}} + V_A^{\text{sea}}\right) \tag{3}$$

where $w^{\rm B}$ is the width of the structure. If $V_{\rm A}^{\rm lee} + V_{\rm A}^{\rm sea} \neq 0$ and $V_{\rm A}^{\rm lee} + V_{\rm A}^{\rm sea} = 0$, $\gamma_2 = 0$. This 3 definition reveals that the DoA is a combination of two aspects: 1) γ_1 is the ratio of the draft 4 to the width of the asymmetric part, reflecting the influence of the horizontal dimension; 2) γ_2 5 is the ratio of the difference between the displacement of the leeward part and the seaward part 6 7 to the total displacement of the asymmetric part, reflecting the inequality between the two 8 components on the two sides of the central line. Straightforwardly, $|\gamma|$ is the absolute 9 asymmetry of the structure. Note that the draft of a breakwater has a great influence on its wave 10 attenuation [14]. The application of DoA and absolute asymmetry should be limited in the comparison between two structures with the same draft, otherwise, the comparison may be 11 meaningless. When $\gamma < 0$, the displacement of the PTO-integrated breakwater mainly 12 concentrates on the seaward side; when $\gamma = 0$, the structure could be symmetric and could be 13 asymmetric with bottom displacement $V_A^{\text{sea}} = V_A^{\text{lee}}$, which is complex with too many parameters 14 and not included in the study; when $\gamma > 0$, the displacement mainly concentrates on the lee 15 16 side.

17 2.2. Governing equation and boundary conditions

18 The float is subjected to a regular wave train with an angular frequency ω traveling in the 19 positive *x*-direction. In the framework of linear potential flow theory, the water flow could be 20 described by the velocity potential

21

24

$$\phi(x, z, t) = \operatorname{Re}[\varphi(x, z)e^{-\mathrm{i}\omega t}], \qquad (4)$$

where $i = \sqrt{-1}$ is the imaginary unit and t denotes time. $\varphi(x, z)$ is the time-independent complex spatial velocity potential that satisfies Laplace's equation,

$$\partial_{xx}\varphi + \partial_{zz}\varphi = 0. \tag{5}$$

25 φ could be decomposed into scattering and radiation potentials, i.e., $\varphi = \varphi_0 - i\omega\xi_3\varphi_3$. The 26 scattering potential φ_0 is the sum of the incident potential φ^I and the diffraction potential 27 φ^D . ξ_3 is the amplitude of response heave motion. φ_3 is the radiation potential due to heave 28 motion of the float with unit velocity. φ satisfies the following linearized boundary conditions, 29 $g\partial_z \varphi = \omega^2 \varphi$, on the free surface z = 0, (6)

30 $\partial_z \varphi = 0$, on the seabed z = -h, (7)

31
$$\partial_n \varphi_3 = n_3$$
, on the fluid and float interface, (8)

 $\varphi^{\mathrm{D}}, \varphi_3$ outgoing; finite value, in the far-field $|x| \to \infty$, (9)

33 where g is the acceleration of gravity, \vec{n} is the unit normal vector on the fluid and float 34 interface, directed into the float, and n_3 is the component of unit normal vector \vec{n} in the 35 heave mode.

- 36 2.3. Explicit expressions for potentials
- The incident velocity potential could be easily expressed following [25],

38
$$\varphi^{I} = -\frac{igA}{\omega} \frac{\cosh[k_0(z+h)]}{\cosh(k_0 h)} e^{ik_0(x-x_0)}.$$
 (10)

where A is the wave amplitude, k_0 is the wavenumber of propagating waves, obeying the dispersion relation $\omega^2 = gk_0 \tanh(k_0h)$. Based on Eqs. (5)-(9) and using the separation of variables, the velocity potential in each subdomain could be given according to [22] and [26].

For i = 1, ..., N and j = 0, 3, 1

2
$$\varphi_{j}^{\Omega_{0}} = \delta_{0j}\varphi^{I} + \left(-\frac{igA}{\omega}\right)^{\delta_{0j}} \begin{bmatrix} R_{0j}^{\Omega_{0}}e^{-ik_{0}(x-x_{0})}Z_{0}(z) + \\ \sum_{m=1}^{\infty} R_{mj}^{\Omega_{0}}e^{k_{m}(x-x_{0})}Z_{m}(z) \end{bmatrix},$$
 (11)

$$\varphi_{j}^{\Omega_{i}} = \left(-\frac{\mathrm{i}gA}{\omega}\right)^{\delta_{0j}} \begin{bmatrix} \varphi_{j}^{\mathrm{p},\Omega_{i}} + \left(S_{0j}^{\Omega_{i}} + T_{0j}^{\Omega_{i}}x\right)Y_{0}^{\Omega_{i}}(z) + \\ \sum_{l=1}^{\infty} \left(S_{lj}^{\Omega_{i}}e^{\lambda_{l}^{\Omega_{i}}x} + T_{lj}^{\Omega_{i}}e^{-\lambda_{l}^{\Omega_{i}}x}\right)Y_{l}^{\Omega_{i}}(z) \end{bmatrix},$$
(12)

4
$$\varphi_{j}^{\Omega_{N+1}} = \left(-\frac{\mathrm{i}gA}{\omega}\right)^{\delta_{0j}} \left[R_{0j}^{\Omega_{N+1}} e^{\mathrm{i}k_{0}(x-x_{N})} Z_{0}(z) + \sum_{m=1}^{\infty} R_{mj}^{\Omega_{N+1}} e^{-k_{m}(x-x_{N})} Z_{m}(z) \right], \quad (13)$$

where δ is the Kronecker Delta function. $\delta = 1$ when the two indices in the subscript are 5 equal and $\delta = 0$ otherwise. $R_{0j}^{\Omega_0}$, $R_{mj}^{\Omega_0}$, $S_{0j}^{\Omega_i}$, $S_{lj}^{\Omega_i}$, $T_{0j}^{\Omega_i}$, $T_{lj}^{\Omega_i}$, $R_{0j}^{\Omega_{N+1}}$, and $R_{mj}^{\Omega_{N+1}}$ (m, l = 16 1, 2,...) are unknown coefficients to be determined. In Ω_0 and Ω_{N+1} , k_m (m = 1, 2,...) is the 7

wavenumber of evanescent waves, obeying the dispersion relation $\omega^2 = -gk_m \tan(k_m h)$ 8 [27]. The corresponding eigenfunctions $Z_0(z)$ and $Z_m(z)$ are defined by 9

10
$$Z_0(z) = \frac{\cosh[k_0(z+h)]}{\cosh(k_0 h)}, \quad Z_m(z) = \frac{\cos[k_m(z+h)]}{\cos(k_m h)}.$$
 (14)

 $\lambda_0^{\Omega_i}$ and $\lambda_l^{\Omega_i}$ (l = 1, 2, ...) are the eigenvalues in the subdomains Ω_i . Subjected to the 11 12 homogeneous boundary conditions on the seabed (Eq. (7)) and the bottom of the asymptotic 13 float while it is static,

$$\partial_z \varphi = 0$$
, on the bottom of the asymptotic float $z = -d_i$, (15)

 $\lambda_0^{\Omega_i} = 0$ and $\lambda_l^{\Omega_i} = l\pi/(h - d_i)$. The corresponding eigenfunctions $Y_0^{\Omega_i}(z)$ and $Y_l^{\Omega_i}(z)$ are 15 16 iven by

14

17

3

$$Y_0^{\Omega_i}(z) = \frac{\sqrt{2}}{2}, \ Y_l^{\Omega_i}(z) = \cos[\lambda_l^{\Omega_i}(z+h)].$$
 (16)

(17)

18
$$\varphi_j^{p,\Omega_i}$$
 is a solution of radiation potential in Ω_i satisfying the non-homogeneous condition in
19 Eq. (8). Based on [22] and [26], it could be expressed as

20
$$\varphi_j^{p,\Omega_i} = \frac{(z+h)^2 - x^2}{2(h-d_i)} \delta_{3j}.$$

2.4. Continuity conditions 21

22 To solve the unknown coefficients in Eqs. (11)-(13), three types of continuity conditions on the interface between each pair of adjacent subdomains at $x = x_i$, i = 0, ..., N, are required. 23 Let \hat{i} denotes the index of $\max(-d_i, -d_{i+1})$, \check{i} denotes the index of $\min(-d_i, -d_{i+1})$. 24 For j = 0, 3, the conditions are as follows: 25

26 1) Continuity of velocity potential on the fluid interface
$$x = x_i$$
, $-h < z < -d_{\tilde{i}}$:
27 $\varphi_i^{\Omega_{\tilde{i}}} = \varphi_i^{\Omega_{\tilde{i}}}$. (18)

27

2) Continuity of horizontal velocity on the fluid interface $x = x_i$, $-h < z < -d_i$: 28

 $\partial_x \varphi_i^{\Omega_{\check{i}}} = \partial_x \varphi_i^{\Omega_{\hat{i}}}.$ 29 (19)

30 3) Continuity of horizontal velocity on the solid boundary
$$x = x_i, -d_{\tilde{i}} < z < -d_{\hat{i}}$$
:
31 $\partial_x \varphi_i^{\Omega_{\tilde{i}}} = 0.$ (20)

1 For simplicity, use eigen_i(z) to represent the eigenfunction in the *i*th subdomain. Thus $\operatorname{eigen}_{0}(z) = \operatorname{eigen}_{N+1}(z) = Z_{m}(z)$. In Ω_{i} , $\operatorname{eigen}_{i}(z) = Y_{i}^{\Omega_{i}}(z)$, $i = 1, \dots, N$. To make the 2 3 equation system a complete set to solve the unknowns coefficients in Eqs. (11)-(13), the 4 velocity potential and velocity terms in Eqs. (18)-(20) need to be multiplied by eigenfunctions 5 and then integrated over the interfaces, i.e., for i = 0, ..., N+1, the integral for Eq. (18) is $\int_{-h}^{-d_{\tilde{i}}} \varphi_{i}^{\Omega_{\tilde{i}}} \operatorname{eigen}_{\tilde{i}}(z) dz = \int_{-h}^{-d_{\tilde{i}}} \varphi_{i}^{\Omega_{\tilde{i}}} \operatorname{eigen}_{\tilde{i}}(z) dz,$ 6 (21)7 and the integral for Eq. (19) and (20) is $\int_{-h}^{-d_{\tilde{i}}} \partial_x \varphi_i^{\Omega_{\tilde{i}}} \operatorname{eigen}_{\hat{i}}(z) dz = \int_{-h}^{-d_{\tilde{i}}} \partial_x \varphi_j^{\Omega_{\tilde{i}}} \operatorname{eigen}_{\hat{i}}(z) dz.$ 8 (22)Substituting the expressions for φ_i in Eqs. (11)-(13) into Eqs. (21)-(22) and truncating the 9 first *M* terms in $R_{mj}^{\Omega_0}$ and $R_{mj}^{\Omega_{N+1}}$ and the first *L* terms in $S_{lj}^{\Omega_i}$ and $T_{lj}^{\Omega_i}$ yield a linear system 10 of 2(M + 1) + 2N(L + 1) complex Eqs for each *j*. 11 12 $\mathbf{A}\mathbf{X}_i = \mathbf{B}_i$ (23)where $\mathbf{X}_j = \left[R_{0j}^{\Omega_0}, \dots, R_{Mj}^{\Omega_0}, S_{0j}^{\Omega_i}, \dots, S_{Lj}^{\Omega_i}, T_{0j}^{\Omega_i}, \dots, T_{Lj}^{\Omega_i}, R_{0j}^{\Omega_{N+1}}, \dots, R_{Mj}^{\Omega_{N+1}} \right]^T$. **A** is the coefficient 13 matrix, which is determined by the shape of the float. The expressions of A and B_i are given 14 15 in Appendix. 16 2.5. Wave excitation force, added mass, and radiation damping 17 The wave excitation forces in the heave could be computed by summing the components in 18 each subdomain, $F_k^{\text{EX}} = \mathrm{i}\omega\rho\sum_{i=0}^{N+1}\int_{\Omega_i}\varphi_0(x,z)n_3ds,$ 19 (24)where ρ is the density of water. 20 21 The radiation force in the kth mode due to the motion in the heave mode could be computed by summing the components in each subdomain, 22 $F_k^{\mathrm{R}} = v_3 f_{k3}^{\mathrm{R}}$ with $f_{k3}^{\mathrm{R}} = \mathrm{i}\rho\omega\sum_{i=0}^{N+1}\int_{\Omega_i}\varphi_3 n_k ds$, 23 (25)where v_3 is the velocity of the float in the heave mode. By some manipulation [22], 24 $F_k^{\rm R} = -a_{k3}\dot{v}_3 + b_{k3}v_3.$ 25 (26)The dot above v_3 denotes the derivative to t. Denote a_{k3} as the added mass and b_{k3} as 26 27 the radiation damping in the kth mode due to the motion in the heave mode which can be written as: 28 $a_{k3} = \frac{1}{\omega} \operatorname{Im}[f_{k3}^{\mathrm{R}}] = \rho \sum_{i=0}^{N+1} \int_{\Omega_i} \operatorname{Re}[\varphi_3] n_k ds,$ 29 (27) $b_{k3} = -\operatorname{Re}[f_{k3}^{\mathrm{R}}] = \rho\omega \sum_{i=0}^{N+1} \int_{\Omega_i} \operatorname{Im}[\varphi_3] n_k ds.$ 30 (28)2.6. Energy conversion efficiency, reflection coefficient, and transmission coefficient 31 32 The motion response ξ_3 of a PTO-integrated breakwater could be solved from the equation 33 of motion in the frequency domain $\left[-\omega^2(m_{33}+a_{33})-\mathrm{i}\omega(b_{33}+b_{33}^{\mathrm{PTO}})+c_{33}\right]\xi_3=F_3^{\mathrm{EX}},$ 34 (29)where $m_{33} = \rho V$, a_{33} , b_{33} , b_{33}^{PTO} , and $c_{33} = \rho g S$ are the mass, added mass, radiation 35 damping, PTO damping, and hydrostatic restoring stiffness of the float, respectively. F_3^{EX} is 36 the wave excitation forces in heave. V is the displacement, and S is the area of the waterplane. 37

1 The time-averaged absorbed power is $P^{\text{ave}} = \frac{1}{2}\omega^2 b^{\text{PTO}} |\xi_3|^2.$

2

The power in the incident per unit width of the wave front is [28]

3 4

$$P^{\text{wave}} = \frac{1}{4} \rho g A^2 \left(1 + \frac{2k_0 h}{\sinh 2k_0 h} \right) \frac{\omega}{k_0}.$$
 (31)

5 The energy conversion efficiency of the PTO-integrated breakwater is

6

10

16

$$\eta = \frac{P^{\text{ave}}}{P^{\text{wave}}}.$$
(32)

(30)

7 The theoretical optimization of the PTO damping and the absorbed power could be obtained while the float is resonant in heave [29]. The results are briefly given as follows without detailed 8 9 derivation.

$$b^{\text{opt}} = \frac{1}{\omega} \sqrt{[(m_{33} + a_{33})\omega^2 - c_{33}]^2 + \omega^2 b_{33}^2},$$
(33)

where b^{opt} is the optimal PTO damping. The optimal absorbed power could be easily 11 computed from Eq. (30). 12

13 While the velocity potential is solved, substitute Eqs.(10)-(13) into the equation of the reflection coefficient $K_{\rm R}$ and the transmission coefficient $K_{\rm T}$, the expressions after 14 simplification are 15

$$K_{\rm R} = \left| \frac{\varphi^{\rm D} - i\omega\xi_3\varphi_3}{\varphi^{\rm I}} \right|_{z=0,x=-\infty} = \left| R_{00}^{\Omega_0} + \frac{\omega^2 R_{03}^{\Omega_0}\xi_3}{gA} \right|,\tag{34}$$

17
$$K_{\rm T} = \left| \frac{\varphi^{\rm I} + \varphi^{\rm D} - i\omega\xi_3\varphi_3}{\varphi^{\rm I}} \right|_{z=0, x=+\infty} = \left| R_{00}^{\Omega_{N+1}} + \frac{\omega^2 R_{03}^{\Omega_{N+1}}\xi_3}{gA} \right|.$$
(35)

18 3. Convergence study and verification

19 In this section, numerical computations are performed to conduct convergence study and 20 validate the proposed semi-analytical method. On the basis of Section 2, the discretization number of breakwater N and the number of truncated eigen-function terms M and L in Eqs.(11) 21 -(13) have a great influence on calculation results, so it is necessary to conduct convergence 22 studies on these parameters. According to Eq. (32), the energy conversion efficiency is equal 23 to P^{ave} over P^{wave} . For the preset wave, P^{wave} is fixed. And as Eq. (30) showed, P^{ave} is in 24 connection with b^{PTO} and ξ_3 . When the optimization of the PTO damping is chosen, b^{opt} 25 26 and ξ_3 are related to added mass, radiation damping and wave excitation force according to 27 Eq. (29) and (33). So added mass, radiation damping and wave excitation force are chosen in 28 convergence study. To validate the present semi-analytical method, a two-dimensional float with left triangular bottom [14], named T-left shown in the Table 1, which has been proved to 29 30 have good wave energy conversion and coastal protection performance, is simulated in this section as an example. And the dimension parameters are shown in the Table 1. The heights of 31 the vertical part and the triangular part are $l_1^B = 5.4$ m and $l_2^B = 1.8$ m, respectively, and the 32 width is $w^{\rm B} = 1.8$ m. 33

34 The present semi-analytical model is validated through three steps. The first step is a 35 convergence test on the bottom shape asymptote. Aiming to eliminate the influence of truncation accuracy with large M and L, set M = L = 200. The added mass, radiation damping, 36 37 and wave excitation force for different numbers of subdomains, N = 8, 15, and 30, are in Figure 2a, b, and c. Results of hydrodynamic coefficients for N = 15 and N = 30 show good 38 39 agreement with a maximum error of 1.03% for added mass, 0.63% for radiation damping, and

- 1 0.57% for wave excitation force, whereas the added mass for N = 8 shows a small deviation
- 2 with a maximum error of 2.02%. Therefore, N = 15 is accurate enough for the float with left
- 3 triangular bottom.

7



Figure 2 A convergence test on the bottom asymptote: comparative results in (a) added mass, (b) radiation damping, (c) wave excitation force

8 The second step is a convergence test on the truncation accuracy. The same model as in the 9 convergence test is used. And the number of subdomains is set as N = 15. The added mass, radiation damping, and wave excitation force for different numbers of truncated terms, M =10 L = 50, 100, and 200, are in Figure 3. Results of hydrodynamic coefficients for M = L = 10011 12 and 200 are almost identical with a maximum error of 0.94% for added mass, 0.25% for 13 radiation damping, and 1.40% for wave excitation force, whereas the added mass and the wave excitation force for M = L = 50 shows a small but obvious deviation, which is 2.89% and 2.83% 14 respectively. Therefore, M = L = 100 is accurate enough for the float with left triangular 15 16 bottom.



Figure 3 Convergence test on the truncation accuracy: comparative results in (a) added mass, (b)
 radiation damping, and (c) wave excitation force

5 The third step is an energy conservation test, as shown in Figure 4. The transmitted, reflected,

and absorbed wave energy is conservative. So the reflection coefficient, transmissioncoefficient and efficiency are accurate.



8 9

Figure 4 Energy conservation relationship

10 4. Effects of PTO damping and geometric asymmetry on the performance of a PTO-

11 integrated breakwater

12 In this section, the effects of PTO damping and geometric asymmetry on the performance of 13 a PTO-integrated breakwater are examined. The water depth is h = 60 m. The period T of the

incident wave is from 4 s to 7 s. The previous study showed the asymmetric float with triangular 1 2 or hemisphere bottom has good wave energy conversion and wave attenuation performance 3 [24][30]. However, the reasons were not given well. To study the effect of asymmetry and the bottom shape on the performance of a PTO-integrated breakwater, six models are used. The 4 5 names of the models and their key dimensions of the immersed parts are shown in Table 1. "Tri" represents a symmetric triangular bottom, "T-" an asymmetric triangular bottom, "Rec" a flat 6 7 bottom, "C-" a circular arc bottom, and "RC-" a reversed circular arc bottom. Similar with Section 3, the convergence study is carried out for all the other five models, M=L=150, 100, 70, 8 9 100, 150 for Tri, T-right, Rec, C-left and RC-left respectively, and N=20, 8, 1, 10, 20 are used 10 in the following calculations.

11

Table 1 Configurations of symmetric and asymmetric PTO-integrated breakwaters

Models	Tri	T-left	T-right	Rec	C-left	RC-left
Cross-section			l_1^{B}			

12 4.1. Effect of PTO damping on wave attenuation

In this section, the influence of the PTO damping b^{PTO} on the transmission coefficient K_{T} is studied to examine if the implantation of a PTO system could improve the wave attenuation of a breakwater. The models 'Tri', 'T-left', and 'T-right' in Table 1 are used. Their drafts are equal. A series of linear PTO damping, $b^{\text{PTO}} = 0$, 10^2 , 10^4 , 10^6 N·s/m and b^{opt} , are applied in each case. b^{opt} is the optimal value of PTO damping at the heaving natural period in each case, obtained by Eq. (33). The key parameters of the models are in Table 2. The results of the transmission coefficient K_{T} for different PTO damping b^{PTO} are displayed in Figure 5.

20

Table 2 Key parameters of Tri, T-left, and T-right models

Models	l_1^{B} (m)	l_2^{B} (m)	<i>w</i> ^B (m)	d _S (m)	d_{A} (m)	γ	Heaving natural period (s)	b ^{opt} (N·s/m)
Tri	6	0.6	1.8	6.6	0	0	5.38	304.14
T-left	6	0.6	1.8	6	0.6	-0.167	5.45	654.32
T-right	6	0.6	1.8	6	0.6	-0.167	5.45	1119.31

In the three PTO-integrated breakwaters, the trends of $K_{\rm T}$ for a given $b^{\rm PTO}$ are quite 21 similar. Asymmetry does not affect the way the PTO damping influencing the wave attenuation 22 of a PTO-integrated breakwater. While $b^{\text{PTO}} = 0$ and $10^2 \text{ N} \cdot \text{s/m}$, K_{T} obtains a trough 23 between T = 5 s and 5.2 s. K_T is about 0 at the trough and is below 0.1 at smaller incident 24 25 wave periods. $K_{\rm T}$ also obtains a peak of about 1.0 at the heaving natural period. While the PTO system is not installed on the breakwater or the PTO damping is small, the wave 26 attenuation of the breakwater is excellent in a range of shorter waves (approximate $T \le 5.2$ s 27 28 in the selected cases). Waves of a particular period could be nearly all blocked. But the situation

1 worsens quickly as the waves become even a little longer. While the incident wave period 2 matches the heaving natural period of the breakwater, the breakwater attenuates little wave energy. The wave attenuation without a PTO system or with a small PTO damping is inferior 3 in longer waves. When $b^{PTO} = b^{opt}$, the local peak still occurs but is much smaller than those 4 of $b^{\text{PTO}} = 0$ and $10^2 \,\text{N} \cdot \text{s/m}$ and the trough vanishes. As b^{PTO} increases to 10^4 and 10^6 5 N·s/m, the pattern of $K_{\rm T}$ further smooths and flattens. The local trough and peak both vanish 6 7 and $K_{\rm T}$ monotonically increases as wave period T increases. While larger PTO damping is 8 applied, wave attenuation is a little worse in shorter waves but the transmission coefficient $K_{\rm T}$ 9 is still below 0.3, whereas the wave attenuation in longer waves is much better. The wave 10 attenuation finally converges as the PTO damping continues to increase.



Figure 5 Effect of the PTO damping b^{PTO} on the transmission coefficient K_{T} for (a) Tri, (b) T-left, and (c) T-right. $l_1^{\text{B}} = 0.6 \text{ m}$, $l_2^{\text{B}} = 6 \text{ m}$, and $w^{\text{B}} = 1.8 \text{ m}$. $b^{\text{PTO}} = 0, 10^2, 10^4, 10^6 \text{ N} \cdot \text{s/m}$ and b^{opt} .

Practically, integrating a PTO system into a floating breakwater to build a hybrid system could not only help foster the extensive and commercial wave energy extraction but also improve the wave attenuation of the breakwater in longer waves, particularly suppressing wave transmission in the region around the heaving natural period.

19 4.2. Effect of asymmetry on energy conversion efficiency and wave attenuation

20 The influence of the DoA γ of a PTO-integrated breakwater on its transmission coefficient 21 $K_{\rm T}$, reflection coefficient $K_{\rm R}$, and energy conversion efficiency η is studied in this part. The 22 models 'Tri', 'T-left', and 'T-right' in Table 1 are used. The dimensions of Tri, T-left, and T-23 right, wave conditions, and water depth are the same as those in Section 4.1, so do their DoA



1 and absolute asymmetry. Here the PTO damping b^{PTO} achieves the optimal value b^{opt} in 2 each case. Results are displayed in Figure 6.

5 Figure 6 Effect of geometric asymmetry on (a) transmission coefficient $K_{\rm T}$, (b) reflection 6 coefficient $K_{\rm R}$, and (c) energy conversion efficiency η of the "Tri", "T-left", and "T-right" PTO-7 integrated breakwaters. $l_1^{\rm B} = 0.6$ m, $l_2^{\rm B} = 6$ m, and $w^{\rm B} = 1.8$ m. The PTO damping in each case takes its 8 optimal value $b^{\rm opt}$.

In Figure 6a, note that K_T^{T-left} and $K_T^{T-right}$ are almost identical and K_T^{Tri} deviates a little 9 from the other two. For a PTO-integrated breakwater with a fixed contour, although the sign of 10 the DoA γ reverses due to the exchange of orientation of the walls, it does not affect the 11 12 absolute asymmetry $|\gamma|$. And while the absolute asymmetry is fixed, the wave attenuation is fixed no matter its orientation. Further, if no PTO system is integrated, according to the 13 conservation relationship $K_T^2 + K_R^2 = 1$, the reflection coefficient K_R is also not affected if the 14 absolute asymmetry is not changed. Note that in the given incident period range, $K_T^{T-left} =$ 15 $K_{\rm T}^{\rm T-right} < K_{\rm T}^{\rm Tri}$ and $|\gamma^{\rm T-left}| = |\gamma^{\rm T-right}| > |\gamma^{\rm Tri}|$. It is observed that larger absolute asymmetry 16 yields slightly better wave attenuation. From the above analysis, the wave attenuation of a PTO 17 18 integrated breakwater relies on the overall geometry and the absolute asymmetry, i.e., no matter 19 the short wall or the long wall of the float facing the incident wave, the transmission coefficient 20 remains unchanged.

In Figure 6b and Figure 6c, a local trough of $K_{\rm R}$ and a local peak of η occur at the heaving natural period of the PTO-integrated breakwater. While the PTO-integrated breakwater is in

resonance, it works well in absorbing the part of wave energy that is not transmitted. Roughly, 1 the relationships of reflection coefficients and the efficiency are that $K_{\rm R}^{\rm T-left} < K_{\rm R}^{\rm Tright}$ 2 and $\eta^{\text{T-left}} > \eta^{\text{Tri}} > \eta^{\text{T-right}}$. T-left has the best and T-right has the worst energy conversion 3 efficiency among the three. As also $\gamma^{\text{T-right}} > \gamma^{\text{Tri}} > \gamma^{\text{T-left}}$, the energy conversion efficiency 4 5 of a PTO-integrated breakwater depends on its DoA. The comparative results show that the DoA does not change the total amount of the reflected and absorbed wave energy but influences 6 7 their proportions. As the DoA increases, i.e., the leeward accumulation of displacement being faster, the proportion of absorbed energy increases, hence the energy conversion efficiency is 8 9 improved.

In application, approaches intending to improve the wave attenuation ability of a PTOintegrated breakwater by merely modifying the contour of the seaward wall without changing the absolute asymmetry may have very limited effort. The structure should be highly asymmetric and the displacement should concentrate on the lee side.

14 5. Approaches to change the geometric asymmetry of a triangular-wedge PTO-

15 integrated breakwater

16 In the previous section, the roles of DoA and absolute asymmetry in the energy conversion efficiency and wave attenuation of a PTO-integrated breakwater have been investigated. It was 17 found that enlarging the absolute asymmetry could improve the wave attenuation and enlarging 18 the DoA could improve the energy conversion efficiency. Here are three approaches to change 19 20 the absolute asymmetry or the DoA of a PTO-integrated breakwater with a triangular-wedge bottom by modifying: 1) the bottom slope, 2) the contour of the wedge, and 3) the width. 21 22 Parametric studies are carried out to 1) demonstrate the feasibility and applicability of the 23 findings in the previous section, and 2) examine the effect of the three approaches in influencing the performance of the PTO-integrated breakwater. 24

25 *5.1. Bottom slope*

The influence of the bottom slope on the energy conversion efficiency and wave attenuation of a triangular-wedge PTO-integrated breakwater is investigated. The models 'Tleft', 'T-right', and 'Rec' in Table 1 are used. Keep the drafts of the models equal. The PTO damping b^{PTO} in each case achieves its optimal value b^{opt} . The key parameters of the selected models are in Table 3. Note that for T-left, the DoA increases as the bottom slope of the structure

31 increases; for T-right, the DoA decreases as the bottom slope increases. Since $K_{\rm T}^{\rm T-left} = K_{\rm T}^{\rm T-right}$

32 for a fixed absolute asymmetry, the results of transmission coefficients of T-left and T-right are

33 collectively given in Figure 7. The reflection coefficient $K_{\rm R}$ and the energy conversion

efficiency η of T-left are in Figure 8. Those of T-right are in Figure 9.

35	Table 3 Key parameters of T-left models with different bottom slope									
	Models	l_1^{B} (m)	l_2^{B} (m)	<i>w</i> ^B (m)	d _S (m)	<i>d</i> _A (m)	γ	Heaving natural period (s)		
	T-left/T-right	6.6	0.6	1.8	6.6	0.6	+/-0.167	5.68		

T-left/T-right	6.0	1.2	1.8	6.0	1.2	+/-0.333	5.55
T-left/T-right	5.4	1.8	1.8	5.4	1.8	+/-0.5	5.41
Rec	$l^{B} =$	7.2 m	1.8	6.3	0	0	5.80

In Figure 7, Figure 8, and Figure 9, the peaks of $K_{\rm T}$, $K_{\rm R}$, and η respectively deviate for different models due to their different natural periods, but one can still find the following facts. As shown in Figure 7, $K_{\rm T}$ decreases as $l_2^{\rm B}$ increases, but the change is not very large, particularly in the regions away from the heaving natural period. The wave attenuation of a PTO-integrated breakwater at the natural period is slightly improved as its bottom slope and absolute asymmetry are increased.

7 In Figure 8 and Figure 9, $K_{\rm R}^{\rm T-left}$ decreases and $\eta^{\rm T-left}$ increases as $l_2^{\rm B}$ increases. $K_{\rm R}^{\rm T-right}$

8 increases and $\eta^{\text{T-right}}$ decreases as l_2^{B} increases. The energy conversion efficiency of T-left 9 and T-right show opposite trends as the bottom slope changes. While the DoA is referred to, the 10 opposite trends reveal the same fact: as the DoA of a PTO-integrated breakwater is enlarged, 11 its energy conversion efficiency is improved, particularly in the narrow region around the 12 heaving natural period. This result is consistent with the findings in the previous section.

To increase the energy conversion efficiency and wave attenuation of a triangular-wedge PTO-integrated breakwater, one needs to make the shorter wall face the incident wave and increase the bottom slope.



16

Figure 7 Influence of bottom slope on the transmission coefficient $K_{\rm T}$ of the "T-left", "T-right" and "Rec" PTO-integrated breakwaters. $l^{\rm B} = 7.2$ m, $l_1^{\rm B} = 6.6$, 6, and 5.4 m, the corresponding $l_2^{\rm B} = 0.6$, 1.2, and 1.8 m, $w^{\rm B} = 1.8$ m. The PTO damping in each case takes its optimal value $b^{\rm opt}$.



Figure 8 Effect of bottom slope on the (a) reflection coefficient $K_{\rm R}$ and (b) energy conversion efficiency η of the "T-left" and "Rec" PTO-integrated breakwaters. $l^{\rm B} = 7.2$ m, $l_1^{\rm B} = 6.6$, 6, and 5.4 m, the corresponding $l_2^{\rm B} = 0.6$, 1.2, and 1.8 m, $w^{\rm B} = 1.8$ m. The PTO damping in each case takes its optimal value $b^{\rm opt}$.



6

1

Figure 9 Effect of bottom slope on the (a) reflection coefficient $K_{\rm R}$ and (b) energy conversion efficiency η of the "T-right" and "Rec" PTO-integrated breakwaters. $l^{\rm B} = 7.2$ m, $l_1^{\rm B} = 6.6$, 6, and 5.4 m, the corresponding $l_2^{\rm B} = 0.6$, 1.2, and 1.8 m, $w^{\rm B} = 1.8$ m. The PTO damping in each case takes its optimal value $b^{\rm opt}$.

11 5.2. Contour of wedge

12 The influence of the bottom wedge contour of a "left" type PTO-integrated breakwater on its 13 energy conversion efficiency and wave attenuation is studied. The models 'T-left', 'C-left', and 14 'RC-left' in Table 1 are selected. The drafts of the models are equal. The PTO damping b^{PTO} 15 in each case achieves its optimal value b^{opt} . The key parameters are given in Table 4. Results 16 of the transmission coefficient K_{T} , the reflection coefficient K_{R} , and the energy conversion 17 efficiency η of T-left, C-left, and RC-left are in Figure 10.



Table 4 Key parameters of T-left, C-left, and RC-left models

Models	l_1^{B} (m)	l_2^{B} (m)	<i>w</i> ^B (m)	$d_{ m S}$ (m)	d_{A} (m)	γ	Heaving natural period (s)
T-left	5.4	1.8	1.8	5.4	1.8	0.5	5.41

C-left	5.4	1.8	1.8	5.4	1.8	0.218	5.57
RC-left	5.4	1.8	1.8	5.4	1.8	0.798	5.35

In Figure 10a, $K_{\rm T}^{\rm RC-left} < K_{\rm T}^{\rm T-left} < K_{\rm T}^{\rm C-left}$ in the region near the natural period. For the three cases, there is the relationship of DoA $\gamma^{\rm C-left} < \gamma^{\rm T-left} < \gamma^{\rm RC-left}$. Then $K_{\rm T}$ decreases as γ increases. In Figure 10b and Figure 10c, it is observed that $K_{\rm R}^{\rm T-left} < K_{\rm R}^{\rm C-left}$ and $\eta^{\rm T-left} > \eta^{\rm C-left}$. $K_{\rm R}^{\rm RC-left}$ and $\eta^{\rm RC-left}$ deviate horizontally a little from their counterparts due to a different heaving natural period. However, one can still approximately consider that $K_{\rm R}^{\rm RC-left} < K_{\rm R}^{\rm T-left} < K_{\rm R}^{\rm T-left} > \eta^{\rm T-left} > \eta^{\rm C-left}$ according to the pattern. As the DoA is increased by applying a revered circular arc bottom contour, the energy conversion efficiency and wave attenuation are improved.

In practice, while using the RC-left design or similar scenario, one can improve the energy
 conversion efficiency and wave attenuation while simultaneously reducing the displacement,
 therefore save the cost of construction material.



Figure 10 Effect of the contour of the wedge on the (a) transmission coefficient $K_{\rm T}$, (b) reflection coefficient $K_{\rm R}$, and (c) energy conversion efficiency η of the "T-left", "C-left", and "RC-left" PTOintegrated breakwaters. $l_1^{\rm B} = 5.4$ m, the corresponding $l_2^{\rm B} = 1.8$ m, $w^{\rm B} = 1.8$ m. The PTO damping in each case takes its optimal value $b^{\rm opt}$.

18 *5.3. Width*

19 In this section, the influence of the width w^{B} of a T-left PTO-integrated breakwater on its 20 energy conversion efficiency and wave attenuation is studied. Here the drafts of the models are 21 equal. The PTO damping b^{PTO} in each case achieves its optimal value b^{opt} . The key 1 parameters are given in Table 5. Note that as w^{B} increases, the DoA γ decreases. Results of

2 the transmission coefficient $K_{\rm T}$, the reflection coefficient $K_{\rm R}$, and the energy conversion

3 efficiency η are shown in Figure 11.

4

Models	l_1^{B} (m)	l_2^{B} (m)	$w^{\mathrm{B}}(\mathrm{m})$	$d_{ m S}$ (m)	<i>d</i> _A (m)	γ	Heaving natural period (s)
T-left	5.4	1.8	1.2	5.4	1.8	0.188	5.52
T-left	5.4	1.8	1.8	5.4	1.8	0.125	5.41
T-left	5.4	1.8	2.4	5.4	1.8	0.094	5.30

Table 5 Key parameters of T-left models with different width

In Figure 11a, the trends of K_T of the three PTO-integrated breakwaters are the same. The 5 horizontal deviation is due to the different heaving natural periods. As w^{B} increases, K_{T} is 6 smaller in shorter waves and longer waves but is more prominent in the narrow region around 7 8 the heaving natural period. Enlarging the width of a breakwater could improve its wave 9 attenuation regardless that the structure is symmetric or asymmetric, which is also observed in previous investigations [14][30]. But the simultaneous decrease of DoA caused by the increase 10 in width will weaken the wave attenuation. In the regions of shorter and longer waves away 11 from the heaving natural period, the variation of width has a more decisive influence than the 12 13 DoA. The improvement in wave attenuation due to the increase of width surpasses the wave attenuation reduction due to the loss of the DoA. Whereas in the region near the heaving natural 14 period, wave attenuation is dominated by the DoA rather than the variation of width. The 15 consequences are therefore reversed. 16

17 In Figure 11b and Figure 11c, the variation of w^{B} does not change K_{R} and η a lot but 18 deviates the heaving natural period. As w^{B} increases, K_{R} increases and η decreases. Like 19 the regularities in wave attenuation, the energy conversion efficiency is weakened in the region 20 around the heaving natural period but is slightly improved in the regions of shorter and longer 21 waves. Besides, increasing the width could move the energy conversion efficiency peak toward 22 longer waves.

23 Considering a flat-bottom PTO-integrated breakwater, enlarging its width will cause no loss 24 in the DoA. Its wave attenuation could be improved in the entire frequency domain and the 25 energy conversion peak will be slightly enhanced and moved toward longer waves, as revealed in Refs [14]. For instance, however, while enlarging the width of a triangular-wedge PTO-26 integrated breakwater, the loss of DoA also happens and causes a reduction in the energy 27 conversion efficiency and wave attenuation, particularly in the region near the heaving natural 28 29 period. Based on the above analysis, while using the variation of the width to change the DoA 30 of a triangular-wedge PTO integrated breakwater, one needs to consider the trade-off between 31 the two contradicting effects carefully. Besides, the change of cost due to the variation of width 32 should also be considered.



3 Figure 11 Effect of the width on the (a) transmission coefficient $K_{\rm T}$, (b) reflection coefficient $K_{\rm R}$, and (c) energy conversion efficiency η of "T-left" breakwater. $l_1^{\rm B} = 5.4 \,\mathrm{m}, \ l_2^{\rm B} = 1.8 \,\mathrm{m}. \ w^{\rm B} = 1.2, 1.8,$ 4 and 2.4 m. The PTO damping in each case takes its optimal value b^{opt} . 5

6 6. Conclusions

The role of geometric asymmetry in the energy conversion efficiency and wave attenuation 7 of a PTO-integrated breakwater was investigated. A 2D frequency-domain semi-analytical 8 9 model dealing with floats with arbitrary bottom shapes is established based on the linear 10 potential flow theory. The method of matching eigenfunction is applied to solve the diffracted and radiated potential. The model is validated against through convergent tests and the law of 11 12 conservation of energy. The concepts of the degree of asymmetry and the absolute asymmetry are introduced and their mathematical expressions are given to quantify and compare the 13 geometric asymmetry of different PTO-integrated breakwaters. The effects of PTO damping, 14 15 degree of asymmetry, and absolute asymmetry on the transmission coefficient, reflection 16 coefficient, and energy conversion efficiency are observed and analyzed. Significant remarks are concluded as follows: 17

18 1) While viscosity is not considered, a bare floating breakwater is nearly useless in 19 attenuating wave energy at its heaving natural period. Applying a PTO-integrated breakwater could improve the wave attenuation in longer waves, particularly near the heaving natural 20 21 period of the system.

22 2) For a PTO-integrated breakwater with a fixed absolute asymmetry, no matter which wall 23 faces the incident waves, the wave attenuation is not influenced. The variation of the degree of asymmetry of an asymmetric PTO-integrated breakwater caused by the exchange of orientation of the two walls does not change the total amount of the reflected and absorbed wave energy but influences their proportions. An increase in the degree of asymmetry improves the energy conversion efficiency and wave attenuation, particularly in the region near the heaving natural period. In order to capture more wave power, the shorter wall of the PTO-integrated breakwater should face the incident wave.

7 3) Based on the findings in the influence of geometric asymmetry, three approaches to modify the energy conversion efficiency and wave attenuation properties of a triangular-bottom 8 9 PTO-integrated breakwater, including changing the bottom slope, the contour of the wedge, and 10 the width, are examined. Increasing the bottom slope could effectively improve energy conversion efficiency and wave attenuation. Using a revered circular arc bottom or similar 11 configuration could improve the energy conversion efficiency and wave attenuation. By 12 increasing the width, the energy conversion efficiency and wave attenuation decline in the 13 region near the heaving natural period but are slightly improved in the regions of shorter and 14 15 longer waves. The peak of energy efficiency could also be moved slightly toward the longer waves. In practical application, one should carefully consider the advantages and disadvantages 16 of the approaches and the consequent manufacturing cost. 17

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23 Appendix

24 The expression of the coefficient matrices **A** in Eq. (23) is

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{M+1,M+1}^{\Omega_{0},\nu} & \mathbf{A}_{M+1,2L+2}^{\Omega_{1},\nu} & & \\ \mathbf{A}_{L+1,M+1}^{\Omega_{0},p} & \mathbf{A}_{L+1,2L+2}^{\Omega_{1},p} & & \\ & \mathbf{A}_{L+1,2L+2}^{\Omega_{1},\nu} & \mathbf{A}_{L+1,2L+2}^{\Omega_{1+1},\nu} & \\ & & \mathbf{A}_{L+1,2L+2}^{\Omega_{1},p} & \mathbf{A}_{L+1,2L+2}^{\Omega_{1+1},p} & \\ & & & \mathbf{A}_{L+1,2L+2}^{\Omega_{N},p} & \mathbf{A}_{L+1,M+1}^{\Omega_{N},p} \\ & & & & \mathbf{A}_{M+1,2L+2}^{\Omega_{N},\nu} & \mathbf{A}_{M+1,M+1}^{\Omega_{N+1},\nu} \end{pmatrix}.$$
(36)

25

In the superscripts, Ω_i means that this part of coefficients are associated with the unknowns in the expression of velocity potential in the subdomain Ω_i , "v" means that the coefficients are for the unknowns to satisfy the conditions of continuous normal velocity, and "p" for continuous pressure. Giving the following definition

30
$$\begin{cases} Q_0 = \int_{-h}^0 Z_0^2(k_0 z) dz = \frac{1}{\cosh^2(k_0 h)} \left(\frac{h}{2} + \frac{\sinh(2k_0 h)}{4k_0}\right), \\ Q_m = \int_{-h}^0 Z_m^2(k_m z) dz = \frac{1}{\cos^2(k_m h)} \left(\frac{h}{2} + \frac{\sin(2k_m h)}{4k_m}\right), \quad m = 1, \dots, M, \end{cases}$$
(37)

the data range of the number of truncated eigen-function terms are that m = 1, ..., M and l = 1, ..., L,

$$\begin{cases} A_{0,0}^{\Omega_{0},v} = -ik_{0}Q_{0}, \\ A_{m,m}^{\Omega_{0},v} = k_{m}Q_{m}, \\ A_{m,l}^{\Omega_{1},v} = e^{\lambda_{l}^{\Omega_{1}}x_{0}}\lambda_{l}^{\Omega_{1}}\int_{-h}^{-d_{1}}Y_{l}(\lambda_{l}^{\Omega_{1}}z)Z_{m}(k_{m}z)dz, \\ A_{m,L+1}^{\Omega_{1},v} = \int_{-h}^{-d_{1}}Y_{0}(\lambda_{0}^{\Omega_{1}}z)Z_{m}(k_{m}z)dz, \\ A_{m,L+l}^{\Omega_{1},v} = -e^{-\lambda_{l}^{\Omega_{1}}x_{0}}\lambda_{l}^{\Omega_{1}}\int_{-h}^{-d_{1}}Y_{l}(\lambda_{l}^{\Omega_{1}}z)Z_{m}(k_{m}z)dz, \\ A_{l,m}^{\Omega_{0},p} = \frac{2}{h-d_{1}}\int_{-h}^{-d_{1}}Z_{m}(k_{m}z)Y_{l}(\lambda_{l}^{\Omega_{1}}z)dz, \\ A_{0,0}^{\Omega_{1},p} = 1, \\ A_{0,0}^{\Omega_{1},p} = e^{\lambda_{l}^{\Omega_{1}}x_{0}}, \\ A_{0,L+1}^{\Omega_{1},p} = e^{-\lambda_{l}^{\Omega_{1}}x_{0}}. \end{cases}$$
(38)

For i = 1, ..., N - 1, the expressions of the submatrix of the coefficient matrices **A** are as follows:

$$\begin{cases} A_{0,0}^{\Omega_{i},p} = \frac{(h-d_{i})}{2}, \\ A_{l,l}^{\Omega_{i},p} = e^{\lambda_{l}^{\Omega_{i}}x_{l}}\frac{(h-d_{i})}{2}, \\ A_{l+1,l+1}^{\Omega_{i},p} = x_{i}\frac{(h-d_{i})}{2}, \\ A_{l+1,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{l}}\frac{(h-d_{i})}{2}, \\ A_{l,0}^{\Omega_{i},p} = \int_{-h}^{-d_{i}}Y_{0}(\lambda_{0}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,0}^{\Omega_{i},p} = e^{\lambda_{l}^{\Omega_{i}}x_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{\lambda_{l}^{\Omega_{i}}x_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = \frac{e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}\int_{-h}^{-d_{i}}Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)Y_{l}(\lambda_{l}^{\Omega_{i}}z)dz, \\ A_{l,l+1}^{\Omega_{i},p} = \frac{e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}(h-d_{i})}{2}, \\ A_{l,l+1}^{\Omega_{i},p} = \frac{e^{-\lambda_{l}^{\Omega_{i}}x_{i}}\lambda_{l}^{\Omega_{i}}(h-d_{i})}{2}, \\ A_{l,l+1}^{\Omega_{i},p} = \frac{(h-d_{i})}{2}, \\$$

4

$$\begin{cases} A_{0,0}^{\Omega_{N},p} = 1, \\ A_{l,l}^{\Omega_{N},p} = e^{\lambda_{l}^{\Omega_{N}}x_{N}}, \\ A_{l,L+1}^{\Omega_{N},p} = x_{N}, \\ A_{l,L+l}^{\Omega_{N},p} = e^{-\lambda_{l}^{\Omega_{N}}x_{N}}, \\ A_{l,m}^{\Omega_{N},p} = \frac{\int_{-h}^{-d_{N}}2Z_{m}(k_{m}z)Y_{l}(\lambda_{l}^{\Omega_{N}}z)dz}{(h-d_{N})}, \\ A_{l,m}^{\Omega_{N},v} = e^{\lambda_{l}^{\Omega_{N}}}\lambda_{l}^{\Omega_{N}}\int_{-h}^{-d_{N}}Y_{l}(\lambda_{l}^{\Omega_{N}}z)Z_{m}(k_{m}z)dz, \\ A_{m,l+1}^{\Omega_{N},v} = \int_{-h}^{-d_{N}}Y_{0}(\lambda_{0}^{\Omega_{N}}z)Z_{m}(k_{m}z)dz, \\ A_{m,L+1}^{\Omega_{N},v} = -e^{-\lambda_{l}^{\Omega_{N}}}\lambda_{l}^{\Omega_{N}}\int_{-h}^{-d_{N}}Y_{l}(\lambda_{l}^{\Omega_{N}}z)Z_{m}(k_{m}z)dz, \\ A_{m,L+1}^{\Omega_{N},v} = -e^{-\lambda_{l}^{\Omega_{N}}}\lambda_{l}^{\Omega_{N}}\int_{-h}^{-d_{N}}Y_{l}(\lambda_{l}^{\Omega_{N}}z)Z_{m}(k_{m}z)dz, \\ A_{0,0}^{\Omega_{N+1},v} = ik_{0}Q_{0}, \\ A_{m,m}^{\Omega_{N+1},v} = -k_{m}Q_{m}. \end{cases}$$

1

7

14

3 The expression of \mathbf{B}_j in Eq. (23) is as follows:

4
$$\mathbf{B}_{j} = \begin{bmatrix} B_{0j}^{x_{0},v}, \dots, B_{Mj}^{x_{0},v}, B_{0j}^{x_{0},p}, \dots, B_{Lj}^{x_{0},p}, B_{0j}^{x_{i},v}, \dots, B_{Lj}^{x_{i},v}, B_{0j}^{x_{i},v}, \dots, B_{Lj}^{x_{i},p}, \dots, B_{Lj}^{x_{i},p}, \dots, B_{Lj}^{x_{i},p}, \dots, B_{Mj}^{x_{i},p}, \dots, B_{Mj}^{x_{i},p} \end{bmatrix}^{T}.$$
 (41)

5 In the superscript, x_i means that the coefficient is associated with the vertical boundary at 6 x_i . In detail,

$$\begin{cases} B_{00}^{x_0,\nu} = -ik_0 Q_0 \\ B_{m0}^{x_0,\nu} = 0, \quad m = 1, ..., M \end{cases}$$
(42)

8 For
$$m = 0, ..., M$$
 and $l = 0, ..., L$,
9 $B_{m3}^{x_0, \nu} =$

$$B_{m3}^{x_0,\nu} = \int_{-h}^{-d_1} \frac{\mathrm{i}\omega x_0}{h-d_1} Z_m(k_m z) dz , \qquad (43)$$

10
$$B_{l3}^{x_0,p} = -\frac{\mathrm{i}\omega}{(h-d_1)^2} \int_{-h}^{-d_1} [(z+h)^2 - x_0^2] Y_n(\lambda_l^{\Omega_0} z) dz, \qquad (44)$$

11
$$B_{l3}^{x_i,\nu} = \frac{\mathrm{i}\omega x_i}{h-d_{\tilde{i}}} \int_{-h}^{-d_{\tilde{i}}} Y_l\left(\lambda_l^{\Omega_{\tilde{i}}}z\right) dz - \frac{\mathrm{i}\omega x_i}{h-d_{\tilde{i}}} \int_{-h}^{-d_{\tilde{i}}} Y_l\left(\lambda_l^{\Omega_{\tilde{i}}}z\right) dz \tag{45}$$

12
$$B_{l3}^{x_{i},p} = \int_{-h}^{-d_{\tilde{i}}} \left(\frac{\mathrm{i}\omega}{2(h-d_{\tilde{i}})} - \frac{\mathrm{i}\omega}{2(h-d_{\tilde{i}})} \right) \left[(z+h)^{2} - x_{\tilde{i}}^{2} \right] Y_{l} (\lambda_{l}^{\Omega_{\tilde{i}}} z) dz , \qquad (46)$$

13
$$B_{l3}^{x_N,p} = -\frac{\mathrm{i}\omega}{(h-d_N)^2} \int_{-h}^{-d_N} [(z+h)^2 - x_N^2] Y_l(\lambda_l^{\Omega_N} z) dz, \qquad (47)$$

$$B_{m3}^{x_N,\nu} = \int_{-h}^{-d_N} \frac{i\omega x_N}{h - d_N} Z_m(k_m z) dz , \qquad (48)$$

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