Performance of an OWC device placed over multi-stepped bottom in random waves environment

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Abstract: The performance of an OWC device placed over multi-stepped bottom is analyzed in random incident waves environment. To model the irregular local wave climate, the Pierson-Moskowitz spectrum along with two different sea states are considered. The effect of chamber width, lip-wall thickness and draft, and turbine damping coefficient of the OWC device on the performance and efficiency are discussed in a detailed manner. It is observed that the OWC device parameters and the local wave climate play a crucial role on the performance and efficiency of the OWC device.

1. INTRODUCTION

The need for the renewable energy has increased over the time due to their eco-friendly nature. Among various renewable energy sources, wave energy has a huge potential to become the ultimate source of energy and convert the same into electricity. Out of various wave power harnessing technologies, the concept of an oscillating water column device (OWC-WEC) is widely used and has a variety of features over other technologies. The mathematical modeling of these OWC devices started since 1980 by several researchers across the world. [1] used BEM method to analyze the performance of an OWC-WEC and it was reported that the configuration of the OWC plays a vital role to enhance the efficiency of the device. [2] studied the hydrodynamics of fully submerged lip wall OWC-WEC. It was found that with an increase in lip-wall draft, the resonance mechanism becomes more prominent. [3] analyzed the performance of an OWC-WEC using Fluent and concluded: (i) the draft of the lip wall is proportional to the period of the optimal efficiency, and (ii) the height of the chamber inversely varies with the efficiency of an OWC-WEC. [4] analyzed the performance of an OWC-WEC placed on the sloping seabed. It was found that for long-wave, the efficiency of an OWC-WEC increases with an increase in chamber length, and opposite phenomena is observed in the short-wave regime. [5] used CFD based technique to determine the efficiency of a single and dual chamber OWC-WEC. [6] studied the effect of structural configurations on the performance of an OWC-WEC, and concluded: (i) the step type bottom diminishes the performance of an OWC device, (ii) the thickness of the lip wall is inversely varies with the bandwidth of the efficiency curve. [7] analyzed the performance of an OWC-WEC placed over the varying bottom. It was concluded that for long waves, the ripple amplitude of the seabed has greater impact on the efficiency of the device. All these works were based on regular incident waves.

In the real sea states, ocean waves are highly random in nature. As a result, the study of the OWC devices under random waves is important. [8] developed the stochastic model to study the working
mechanism of an OWC-WEC. [9] analyzed the performance of an OWC-WEC under the random waves. [10] used nonlinear approach to analyze the performance of an OWC-WEC. It was shown that the compressed air and viscosity significantly impact the efficiency of the device. [11] developed an algorithm to optimize the configurations of an OWC-WEC under the action of random waves. [12] analyzed the efficiency of an OWC-WEC placed over the stepped bottom in random waves environment. The authors showed that the incident wave frequency and the turbine damping coefficient are the key parameters to control the efficiency of an OWC device. [13] analyzed the efficiency of an L-shaped OWC device in random waves environment and showed that the amplification factor and the efficiency of an OWC-WEC mainly depend on the lip-wall draft. [14] studied the efficiency of an OWC-WEC in random waves environment. It was observed that the incident wave spectrum strongly influences the spectrum generated inside the chamber. Recently, [15] proposed a new design of the OWC device by introducing a moving front in the device and found that the proposed design modifications can enhance the efficiency of the device significantly. [16] investigated the effect of seabed slopes and incident wave steepness on the efficiency of an OWC-WEC. The study reveals that for linearized water waves, the peak in the efficiency of the OWC-WEC becomes lower for wider device chamber.

In the present study, the performance of an OWC device placed over multi-stepped bottom is analyzed under irregular incoming waves. The paper is structured as follows. Firstly, the mathematical formulation is given. Thereafter, the expressions of the key parameters associated with the OWC device performance are given. Finally, the results and conclusions are provided.

2. MATHEMATICAL FORMULATION

The current study yields the mathematical modeling of an OWC-WEC placed over the multi-stepped bottom. Here, 2D Cartesian coordinate system is used. The OWC-WEC constitutes a rigid and impenetrable thick lip wall of uniform thickness $d$ and stood at $x = L - b$. Here, $b$ denotes the chamber width and the lip wall of the OWC-WEC consists of two vertical walls having heights $a_1$ and $a_2$ respectively. Moreover, the rear wall of an OWC-WEC is positioned at $x = L$. The OWC device is placed over the multi-stepped bottom with the step-length $b/4$ over the range $\{L - b < x < L\}$ and the seaside region of the lip wall has uniform water depth $h_1$. The mean free surface has two components $\Gamma_f$ (external free surface) and $\Gamma_i$ (internal free surface). To close the domain, an auxiliary boundary $\Gamma_b$ is considered at $x = -l$. Further, $\Gamma_b$ represents the bottom boundary, and $\Gamma_{d1}$ and $\Gamma_{d2}$ are the rigid boundaries as seen in Fig. 1. The water motion is governed by the potential flow theory and also assumed to be time harmonic in nature. So, the total velocity potential is splitted into spatial and time dependent parts as $\Phi(x, z, t) = \text{Re}\{\phi(x, z)e^{-i\omega t}\}$, and the governing equation is given by

$$\nabla^2 \phi(x, z) = 0 \tag{1}$$
Here, $\phi = \phi^S + \phi^R$ with $\phi^S$ and $\phi^R$ satisfy the bc at $z = 0$ and therefore

$$\frac{\partial \phi^{S,R}}{\partial n} - K \phi^{S,R} = \begin{cases} \Xi, & \text{on } \Gamma_{f2}, \\ 0, & \text{on } \Gamma_{f1}. \end{cases}$$

(2)

Here, $K = \omega^2/g$, and $\Xi = 0$ for $\phi^S$ and $\Xi = 1$ for $\phi^R$ respectively. The no-flow boundary condition on $\Gamma_b \cup \Gamma_{d1} \cup \Gamma_{d2}$ is given by

$$\frac{\partial \phi^S,R}{\partial n} = 0, \text{ on } \Gamma_b \cup \Gamma_{d1} \cup \Gamma_{d2}$$

(3)

The radiation boundary condition on $\Gamma_l$ is given by

$$\frac{\partial \phi^S,R}{\partial n} - i k_0 \phi^S,R = \delta \left( \frac{\partial \phi^l}{\partial n} - i k_0 \phi^l \right), \text{ on } \Gamma_l$$

(4)

Here $k_0$ is the progressive wave mode and $\phi^l$ is given by $\phi^l(x, z) = \frac{-i g A}{\omega} \cosh k_0(z - h) \cosh(k_0 h) e^{ik_0 x}$ and $A$ is termed as incident wave amplitude. In Eq. (4), $\Xi = 1$ for $\phi^S$ and $\Xi = 0$ for $\phi^R$ respectively.

The aforementioned BVP is solved using the BEM. The Green's function $G(x, z; r, s)$ is given as

$$G(x, z; r, s) = -\frac{1}{4\pi} \sqrt{(x - r)^2 + (z - s)^2}.$$  

(5)

Using Green's identity on $G(x, z; r, s)$ and $\phi^{R,S}$, and using the Eqs. (2)-(4), the following FIE are obtained

$$\frac{1}{2} \phi^R + \int_{\Gamma_1} \phi^R \left( \frac{\partial G}{\partial n} - i k_0 \phi^S \right) d\Gamma + \int_{\Gamma_{f1} + \Gamma_{d1} + \Gamma_{d2}} \phi^R \frac{\partial G}{\partial n} d\Gamma + \int_{\Gamma_{f2}} \phi^R \left( \frac{\partial G}{\partial n} - K G \right) d\Gamma$$

$$+ \int_{\Gamma_{f1}} \phi^R \left( \frac{\partial G}{\partial n} - K G \right) d\Gamma = \int_{\Gamma_{f2}} G d\Gamma$$

(6)

$$\frac{1}{2} \phi^S + \int_{\Gamma_1} \phi^S \left( \frac{\partial G}{\partial n} - i k_0 \phi^S \right) d\Gamma + \int_{\Gamma_{f1} + \Gamma_{d1} + \Gamma_{d2}} \phi^S \frac{\partial G}{\partial n} d\Gamma + \int_{\Gamma_{f2}} \phi^S \left( \frac{\partial G}{\partial n} - K G \right) d\Gamma$$

$$+ \int_{\Gamma_{f1}} \phi^S \left( \frac{\partial G}{\partial n} - K G \right) d\Gamma = \int_{\Gamma_{f2}} G \left( \frac{\partial \phi^l}{\partial n} - i k_0 \phi^l \right) d\Gamma$$

(7)

Now, Eqs. (6)-(7) are solved using the BEM method to determine $\phi$ and $\partial \phi/\partial n$. The details are available in [7].

3. IRREGULAR WAVES ENVIRONMENT

Real ocean waves are represented using appropriate wave spectrum and sea-states. Here, the Pierson-Moskowitz spectrum [17] is used, and the form is given by

$$SP_i(\omega) = 263H_s^2 T_e^{-4} \omega^{-5} \exp(-1054T_e^{-4} \omega^{-4})$$

(8)

The standard deviation $\sigma_p$ of the chamber pressure is given by (see [15] for details)

$$\sigma_p^2 = \int_0^\infty SP_i(\omega) \left( \frac{P_r(\omega)}{\text{amp}(\omega)} \right)^2 d\omega,$$

(9)

where $\text{amp}(\omega) = \sqrt{2SP_i(\omega) \delta \omega}$ is the incident wave amplitude for regular wave component. Here, $SP_i$ represents the incident wave spectrum. The average efficiency of an OWC device is given by

$$\zeta_A = \frac{W_A}{P_A},$$

(10)

where $W_A$ and $P_A$ are termed as average available power to the Wells turbine and the incident wave energy flux respectively and are expressed as

$$P_A = \rho g \int_0^\infty SP_i(\omega) C_g(\omega) d\omega,$$

(11)
\[ W_A = \tau \eta^2. \]  

(12)

Here, \( C_g \) and \( w \) are the group velocity of the incoming wave and the chamber width. Moreover, \( \tau \) is the turbine damping coefficient.

4. RESULTS

The parameters related to the incoming waves and OWC device are the following: \( h_1 = 10 \text{m}, h_2 = 0.7 h_1, \rho = 1025 \text{kg/m}^3, g = 9.81 \text{m/s}^2, L = 3 h_1, b = 2 h_1, l = 3 h_1, a_1 = 0.4 h_1, a_2 = 0.2 h_1, \) \( d = 0.05 h_1 \) unless mentioned. The characteristics of two most occurrence sea states for the incoming wave spectrum as in Eq. (8) are the following (see [17] for details): the significant wave \( H_s = 1.88 \text{m}, 3.18 \text{m} \) and the associated periods \( T_e = 6.33 \text{s}, 9.93 \text{s} \).

Figs. 2(a) and 2(b) demonstrate the fluctuation of free surface elevation \( z \) for different (a) chamber length \( b/h_1 \) and (b) submergence depth \( a_1/h_1 \) respectively. It is seen that with an increase in \( b/h_1 \), the amplitude of elevation \( \zeta \) becomes lower. Further, certain phase change in \( \zeta \) is observed for different \( b/h_1 \). However, the amplitude of \( \zeta \) increases in the open water region with an increase in \( a_1/h_1 \), and opposite pattern is observed within the chamber. Moreover, a phase change in \( \zeta \) occurs for various \( a_1/h_1 \).

Figs. 3(a) and 3(b) demonstrate the variation of \( \zeta \) for different (a) \( a_2/h_1 \), and (b) \( d/h_1 \), respectively. It is noticed that \( \zeta \) does not alter much with the variation in \( d/h_1 \) and \( a_2/h_1 \). The happens as the wave energy is mostly concentrated near the free surface and so, the effect of bottom variation on \( \zeta \) is insignificant.
Fig. 4. $\zeta_A$ vs $\tau$ for various $b/h_1$ with (a) $H_s = 1.88m, T_e = 6.33s$ and (b) $H_s = 3.18m, T_e = 9.93s$

Figs. 4(a) and 4(b) illustrate the average efficiency $\zeta_A$ vs $\tau$ for different $b/h_1$ for first and second seastates. It is seen that for first sea state, efficiency $\zeta_A$ decreases as $b/h_1$ increases. However, for second sea state, $\zeta_A$ increases as $b/h_1$ takes higher values. This suggests that the efficiency of the OWC strongly depends on the sea states.

Fig. 5. $\zeta_A$ vs $\tau$ for various $a_1/h_1$ with (a) $H_s = 1.88m, T_e = 6.33s$ and (b) $H_s = 3.18m, T_e = 9.93s$

Figs. 5(a) and 5(b) show $\zeta_A$ vs $\tau$ for various $a_1/h_1$ for first and second sea states. In both the cases, $\zeta_A$ decreases as $a_1/h_1$ increases. This happens because the wave energy gets reflected by the front wall as the draft of the front wall becomes higher. As a result, less wave energy enters into the OWC chamber.

Fig. 6. $\zeta_A$ vs $\tau$ for various $a_2/h_1$ with (a) $H_s = 1.88m, T_e = 6.33s$ and (b) $H_s = 3.18m, T_e = 9.93s$
Figs. 6(a) and 6(b) demonstrate $\zeta_A$ vs $\tau$ for different $a_2/h_1$ for the first and second sea states. In both cases, efficiency $\zeta_A$ decreases as $a_2/h_1$ takes higher values. The reason for the same is already provided in the previous figures.

Figs. 7(a) and 7(b) show $\zeta_A$ vs $\tau$ for various $d/h_1$ for first and second sea states. It is noticed that the efficiency $\zeta_A$ decreases as various $d/h_1$ becomes higher. The rationale for this is already provided in the previous figures. Further, the efficiency $\zeta_A$ is much higher for second sea state compared to the first sea state. This happens as the wave height is higher in second sea state and so it contains higher amount wave energy.

5. CONCLUSIONS

In the present study, the average efficiency of an OWC device placed over multi-stepped bottom is analyzed in irregular waves environment. To model the irregular incoming waves, the Pierson-Moskowitz spectrum along with two different most frequently occurred sea states are taken into account. It is noticed that the efficiency of the OWC decreases as the lip-wall draft and thickness increases. In the first sea state, the efficiency decreases as chamber length increases and reverse results are observed for the second sea state. Moreover, the amplitude of surface elevation increases in the open water region with an increase in lip-wall draft and opposite trend is seen inside the OWC chamber. In addition, certain phase changes occur in the free surface displacement for various lip-wall draft and chamber width.

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