Three-dimensional effects on the performance of multi-level overtopping wave energy converter

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Abstract
The performance of a multi-level overtopping wave energy converter has been numerically investigated in a three-dimensional wave tank. The device has three extra slots and is positioned on a breakwater. The span length of the breakwater is the main parameter associated with the three-dimensional effects on the hydraulic efficiency of the wave energy device. It has been shown that the device with a finite span yields a lower captured crest energy due to waves falling-down the edges during the run-up process. The result also implies that as the span of the device is increased, the efficiency tends to increase further to resemble the two-dimensional device. The three-dimensional mechanism has a significant influence on the potential energy in the water being stored by the higher reservoirs, while that of lower ones have relatively smaller effects. In addition, a relation between hydraulic efficiencies of two and three-dimensional devices has been proposed.

1. Introduction
Nowadays, the carbon dioxide (CO2) emission from combustion engines in transportation and industrial sectors causes the air pollution crisis in many cities such as Delhi, Seoul, Chiang Mai, and central and eastern China [1–4]. Subsequently, researchers have been seeking for methods in order to resolve the crisis. As a result, the development of renewable energy technology is considered as an option to alleviate the air pollution problem as well as energy shortage and crisis. The utilization of renewable energy seemingly contributes to the reduction of greenhouse emission level [5].

Harvesting renewable energy is significantly advantageous since it generally replenishes. However, the utilization of renewable energy is currently minor compared to total energy consumption. Particularly, the hydropower holds the largest share of worldwide renewable energy utilization with increasing tendency every year, while the electricity generation from ocean renewable energy is relatively small [6]. Nevertheless, ocean energy resources are considerably huge and predictable. Scientists and engineers have consequently been working to innovate ocean energy technology, e.g., tidal current turbines, offshore wind turbines, and wave energy converters.

Wave energy converters (WECs) are various in design and can be categorized according to their principles in the energy capture process, e.g., oscillating device, oscillating water column (OWC), and overtopping wave energy converter (OWEC). The overtopping devices collect and accumulate wave
energy in the form of the potential energy of stored water volume in a reservoir which has the mean water level higher than the sea level. The stored water is simultaneously released back to the sea through a tube or channel in which a low head turbine is typically installed to extract the energy.

Optimization of geometric design yielding a high-volume flow rate into the reservoir has been one of the main interests for the OWEC studies. The OWEC originally possesses only one reservoir. This results in a relatively low efficiency since the ocean conditions are noticeably variable and the single-level device could deliver its best efficiency only at a specifically designed condition. An example of the single-level OWEC is the Wave Dragon [7-9]. Generally, the hydraulic efficiency of an OWEC, based on the single-level design, can be 20-30% approximately. A multi-level configuration has therefore been proposed for the performance enhancement in a wider range of tidal and wave conditions.

Several experimental and numerical investigations [10-14] have been performed to better understand the unsteady hydrodynamic mechanisms in wave overtopping behavior. It is difficult to capture all physical aspects of the flow by performing only experiments. Therefore, numerical simulations are mainly used to preliminarily study and efficiently find out the optimal design. Experimental and numerical studies concerning OWECs have mainly been conducted based on two-dimensional flow. In the present study, numerical simulations of multi-level OWEC integrated with breakwaters are performed in a three-dimensional wave tank. This study investigates the influence of the breakwater span length on hydraulic efficiency. The results obtained from this study are compared with that of a two-dimensional OWEC. Flow physics and overtopping mechanisms have been additionally discussed.

2. Materials and Methods

The numerical tool used to investigate the wave overtopping behavior of a multi-level OWEC device is a commercial CFD solver ANSYS FLUENT V17. The governing equations are the continuity and the Reynolds Average Navier-Stokes (RANS) equations for viscous, incompressible, three-dimensional flow. The standard \( k - \varepsilon \) turbulence model is applied for turbulence closure while the free surface is tracked and located using the two-phase volume of fluid (VOF) method proposed by [15].

![Figure 1](image_url). The three-dimensional numerical wave tank used to simulate wave overtopping behavior.
2.1 Numerical Wave Tank
The wave overtopping behavior is simulated in a three-dimensional numerical wave tank as shown in Figure 1, which has a water depth of $d = 20$ m and a tank length of 300 m, approximately corresponding to $0.36\lambda$ and $5.4\lambda$ respectively, where $\lambda$ is the wavelength. Wall conditions, combined with a dynamic mesh model, is utilized on the left boundary, which acts as a piston-type wavemaker. As for the right boundary, the pressure outlet combines with the open channel flow condition is applied. In order to reduce the domain size and number of meshes, the symmetric plane is utilized. The first-order linear wave is generated as an incident wave. In order to prevent an impulsive movement at the beginning, the kinematics of the piston type wavemaker $x(t)$ is defined by the following:

$$x(t) = \frac{x_0}{2} \left( 1 - e^{-\frac{5t}{T}} \right) \sin \omega t$$

(1)

where $x_0$ is the maximum displacement of the wavemaker, yielding the desired wave height, and $\omega$ is the angular frequency relevant to the wave period.

2.2 Wave Energy device and Ocean conditions
The sectional layout is based on a multi-level OWEC used by [10] integrated with breakwater, which is schematically illustrated in Figure 1 and 2. The device consists of a ramp of slope $S = 1/2$, together with extra slots at different levels which are connected to corresponding reservoirs. The width of these slots is identical as $w = 0.4$ m. The crest height of the lowest reservoir is $R_{c1} = 0.5$ m, while that of the higher ones have a constant increment of 0.5 m. The crest of the main reservoir is, therefore, $R_{c4} = 2.0$ m.

![Figure 2. Sectional layouts of the OWEC device. The incident wave direction is from left to right](image)

In order to study the influence of span length $L_B$ on the performance of the device, the parameter is varied within the range of $0.5\lambda \leq L_B \leq 2.0\lambda$ with a $0.5\lambda$ increment. The generated incident wave height $H = 2$ m, together with wave period $T = 6$ s is utilized following [10]. This combination yields the wave steepness $H/\lambda = 0.036$, the relative wave height $H/d = 0.1$, and the relative slot width, $w/R_{c4} = 0.2$.

2.3 Discretization of Numerical Model
A grid system of the computational domain has been generated with adaptive refinement. A dense, more refined mesh is applied and generated in regions of interest which are the vicinity of the free surface and the OWEC device, especially near the slots and the tip of the device.

![Figure 3. The Surface mesh of the multi-level OWEC device](image)
The mesh size is dependent on wave height and length. The number of cells per wave height is 20, in combination with 100 cells per wavelength. The current discretization is finer than the suggestion from [16]. The time step size is \( dt = T/6000 \). It has been found that the larger time step of \( dt = T/3000 \) yields a slight deviation in the simulated overtopping discharge compared to \( dt = T/6000 \) case.

2.4 Wave Energy Conversion Performance

In order to generate electricity from wave energy using overtopping principle, the wave energy is firstly captured and collected in potential form in a reservoir. The potential energy of stored water is then converted to mechanical energy via a low-head turbine and consequently transformed into electricity by a generator. These energy conversion processes correspond to hydraulic, reservoir, turbine and generator efficiencies respectively. In this study, the hydraulic efficiency \( \eta \) is used to present the performance of the wave energy device. This performance indicator is also known as the capture width ratio (CWR).

\[
\eta = \frac{P_{\text{crest}}}{L_B P_{\text{wave}}} = \frac{\sum_{i=1}^{n} Q_i \rho g R_{c,i}}{L_B \frac{1}{16} \rho g H^2 c \left[1 + \frac{2k d}{\sinh(2kd)}\right]} 
\]

where \( P_{\text{crest}} \) is the rate of overtopping energy captured by the device, \( P_{\text{wave}} \) is the wave energy per unit width, \( Q_i \) is the time-averaged overtopping flow rate of the corresponding \( i^{th} \) reservoir, \( \rho \) is the water density, \( g \) is the gravitational acceleration, \( R_{c,i} \) is the crest height of the \( i^{th} \) reservoir, \( H \) is the incident wave height, \( c \) is the phase velocity, \( k \) is the wave number, and \( d \) is the water depth. The parameter \( L_B \) is the span length of the wave energy device which is the independent variable of primary interest.

3. Results and Discussion

The hydraulic efficiency of the three-dimensional device with different dimensionless spans is compared with a two-dimensional device in Figure 4. Note that the two-dimensional device has an infinite span \( L_B/\lambda = \infty \). Clearly, the three-dimensional effects play an important role in the wave energy capture mechanisms. The device with the shortest span yields the lowest relative efficiency, while increasing the span length yields greater performance. Another increase in span length resulted in a further performance enhancement, which tends to converge with a device with an infinite span, i.e., the two-dimensional device, as presented by the overall hydraulic efficiency in Figure 4(a).

![Figure 4. Hydraulic efficiency \( \eta \) as a function of dimensionless span \( L_B/\lambda \).](image-url)
This mechanism is analogous to the difference between two and three-dimensional wings, as a wider aspect ratio yields a greater lift coefficient, a shorter one results in a lower lift coefficient due to three-dimensional vortices generated at wing tips. Similarly, the three-dimensional OWEC model has a finite span possessing tips, which leads to waves falling-off the edges during the run-up process as seen in Figure 5. As a result, a wave at the tip of the device cannot run-up as high as a wave near the centerline. This consequently leads to a drastic decrease in partial efficiency of the main reservoir, whereas the effects are in-determinant for reservoirs with a relatively low crest level. It is subsequently suggested to install a guide vane at the tips of the device, which could prevent or reduce the three-dimensional effects and increase the effective span of the device, similar to what winglets achieve on an aircraft.

![Figure 5](image)

**Figure 5.** Top-view snapshots of wave flow into reservoirs at time $t$, $t + 0.2T$, $t + 0.4T$, $t + 0.6T$, $t + 0.8T$ respectively from left to right. The wave direction is from left to right

Figure 4(b) shows the partial hydraulic efficiencies for different reservoir levels. When the span length is increased, the enhancement in partial hydraulic efficiency varies depending on the level of the reservoirs. Within the parametric range considered, the span length may have no significant influence on the potential energy stored in the lowest reservoir, since the partial hydraulic efficiency seems to change unnoticeably. However, the potential energy stored in the main reservoir, i.e., the highest one, is seemingly more sensitive to the change in span length.

In addition to the numerical results, an approximation used to predict the relationship between two- and three-dimensional partial hydraulic efficiencies of this multi-level OWEC device has been proposed.
The three-dimensional partial efficiency $\eta_{i}^{3D}$ can be expressed as a function of the dimensionless span $L_B/\lambda$ and the two-dimensional partial efficiency $\eta_{i}^{2D}$ as:

$$\eta_{i}^{3D} = \frac{L_B/\lambda}{L_B/\lambda + Z_i} \cdot \eta_{i}^{2D} \tag{3}$$

where $Z_i$ is a factor used to fit the curve. This factor could be a function of wave steepness, water depth, or the geometry of the device such as slope ratio, slot width, or the crest height of the $i$th reservoir. In figure 6, the partial hydraulic efficiencies are plotted along with the prediction corresponding to equation (3). The values of $Z_1$, $Z_2$, $Z_3$ and $Z_4$ are 0.0757, 0.1635, 0.2440 and 0.3923 respectively. It should be noted that the smaller value of $Z_i$ gives a more rapid convergence to the efficiency of the device with an infinite span. The proposed formula, combined with an appropriate value of $Z_i$, appears to sufficiently predict the convergent trend of hydraulic efficiency in spite of a slight deviation.

**Figure 6.** Partial hydraulic efficiencies obtained using two and three-dimensional models. The solid line represents the approximation of partial hydraulic efficiency $\eta_{i}^{3D}$ of the device with a finite span as a function of dimensionless span $L_B/\lambda$. 
4. Conclusion
This study aims at conversion and utilization of wave energy using the overtopping principle. A numerical model for three-dimensional flow was used to investigate the effects of span length of multi-level overtopping wave energy devices on energy captured. The hydraulic efficiency of the three-dimensional device is compared with the baseline two-dimensional device. A convergent trend is found for the relation between span length and hydraulic efficiency, both overall and partially. As for the device with a relatively narrow span, an increase in span length gives a huge enhancement in the hydraulic efficiency. However, the hydraulic efficiency is slightly affected by the change in span length when the device is relatively wide. Moreover, a formula used to predict the relation between efficiencies of two and three-dimensional devices has been proposed which appears to be valid with acceptable accuracy.

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