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Wave Transformation on Wave Catcher Shore Protection – Dual Slope (WCSP-DS) Zig-Zag Model with Wave Focused Wall

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Abstract. The Wave Catcher Shore Protection Dual Slope (WCSP-DS) is a coastal structure with a dual function of shore protection and wave power generation. The WCSP-DS structure captures seawater through overtopping into the crest reservoir resulting in a higher reservoir water level than the sea. This elevation difference will be the pressure height (head) and is represented by the freeboard height (Fb) and together with the overtopping discharge unit (q) will be the main parameter for electrical power. This study aims to increase the discharge value (q) at the maximum freeboard height (Fb) through engineering effort in the wave transformation process by adjusting the setting position of the WCSP in a zig-zag manner and adding a wave-focused wall (WFW) to produce a maximum deformed wave height (Hdf) in front of the WCSP-DS. Located in Hasanuddin University's Coastal & Environmental Engineering Laboratory, the study was carried out experimentally using geometrically scaled 1:20 physical model simulations. Three Dimensional (3D) wave basins in the size of 10 m x 15 m x 1 m equipped with an automatic wave generator and data recording instrument were utilized. Two type models namely the M1 (without collector) and the M2 (with collector) were simulated with relative water depth (d/z), freeboard height (Fb), incoming wave height, and period (Hi & T). The results indicated that the deformed wave height (Hdf) increased significantly ranging from 300% to 900% on M1 and from 350% to 1100% on M2. The increase in the value of Hdf also increases the discharge (q) that enters the reservoir. By these results, a combination of Fb and q can be selected which can generate optimal electrical power.

1. Introduction

Indonesia is a maritime country where 2/3 of its territory is the sea and has the second longest coastline in the world, and therefore, Indonesia has a large potential for marine energy such as wave energy, currents, tides, and temperature differences. These potentials have not been fully exploited and Indonesia has so far relied on fossil energy and coal, whose availability is dwindling. In conditions of increasing demand and the availability of abundant non-renewable energy sources, It is time to create new renewable energy sources, and the sea wave is one of those sources. The wave energy is a function of the wave height and period [1]. These two parameters thus assume a crucial role. In particular, for port cities and remote islands in Indonesia, the characteristics of wave energy sources are very suitable to be developed to meet energy needs. Due to the energy transfer process from the wind in the generating area, sea waves are one of the hydrodynamic activities that occur in the sea and on beaches [2]. The waves that travel along the coast from deep waters to shallow waters have a lot of energy, sometimes even enough that it is known that the wave has a lot of destructive power. Large and expensive breakwaters may occasionally be required to be built to destroy the wave energy in order to protect coastal areas and certain port areas. This paradigm appears to be out of date and needs to be modified to reflect the circumstances of both the present and the future. It is essential to create a multifunctional coastal protection system that serves as both a wave power plant and a barrier against wave attack [3].

Except for Indonesian waters bordering the Indian Ocean, which have not been developed, research and exploration efforts on the use of wave energy have been made in many regions of the world, particularly in the Pacific Ocean ring area, Atlantic Ocean, and the Indian Ocean. According to information, there are places with a sufficient wave energy potential ranging from 10 to 20 kW per wave meter along the South Coast of Java to Nusa Tenggara. According to the findings of several studies, wave energy at some locations in Indonesia can reach 70 kW/m. Additionally, the southern coast of Java Island's western portion and the west coast of Sumatra Island both have potential wave energy of about 40 kW/m [4].

The generation of intermittent electric current poses a number of challenges for the development of wave power plants, necessitating the use of adequate infrastructure and technology to ensure stability. Another barrier is that it costs a lot of money to build a wave power plant, which makes electricity more expensive and makes it difficult for it to compete with on-land power plants [5]. In order to lower the investment cost, it is therefore important to consider multiple functions for the wave energy conversion rather than just one.

This study is a component of work on the Zig-Zag Model Wave Catcher Shore Protection, also known as the Overtopping Wave Energy Converter (OWEC) (WCSP-DS). WCSP-DS Zig-Zag model is a model of a coastal protection structure in the form of a caisson box with dual slopes on the front wall, namely 45^{o} slope of the upper wall and 90^{o} or upright at the sub wall [6]. The combination slopes of this wall are intended to accommodate wave runups that can produce large volumes of overtopping to be accommodated in the crest reservoir. This research is the development of a series of OWEC breakwater studies studied by Thaha et al at the Research Center for Coastal Engineering, Faculty of Engineering, Hasanuddin University, Indonesia [7],[8],[9], and [10]. The two problems mentioned above are the focus of the entire research series. Because wave potential energy is used, the OWEC type can overcome the instability of the electric current produced. While waiting, a multipurpose coastal structure can be built to solve the issue of financial inadequacy. Engineering efforts to produce a wave transformation that generates a large wave height (H) in front of the model structure are one of the significant aspects that are being studied. It is anticipated that the maximum wave height will generate a significant overtopping discharge, increasing the amount of wave energy that can be captured and used to turn the turbine.

1.1. Problem Formulation & Research Objectives

The new paradigm that underlies this series of research is to change the working mechanism of the breakwater from destroying energy to capturing wave energy in its function of protecting the coast. The captured potential energy is then flowed to turn a turbine to produce electrical power. The amount of energy that can be utilized depends on the amount of overtopping discharge that can be caught. The magnitude of the overtopping discharge is determined by the height of the breaking wave on the WCSP-DS wall. The height of the deformed waves that arrive at the structure model that travels from the deep sea determines the height of this breaking wave. The zig-zag setting shape of WCSP-DS and the installation of a wave-focused wall under shoaling conditions are the two main factors that will be examined in this study to determine the extent to which the deformed wave height (Hdf) will increase.

2. Literature Review

2.1. Wave Energy Converter

The wave-activated body, point absorber, oscillated water column, and overtopping are the four concepts that have been successfully applied to convert wave energy. According to Lopez in Puspita et al., the point absorber type of WEC is the most widely used and developed, whereas the overtopping WEC is the less developed type. The Overtopping Wave Energy Converter (OWEC) converter works on the principle of accommodating the overtopped water into the reservoir, where potential energy is then transformed into mechanical energy by a turbine from the reservoir at the top of the converter with an elevation higher than sea level (Figure 1). The first overtopping-related invention was Tapered Chanel technology, or simply Tapchan (Figure 1). The first WEC overtopping sink of this kind was created in Norway in 1980. The principle used in Tapchan is similar to that of traditional hydroelectric power, in which ocean waves are concentrated into the reservoir through an overtopping mechanism and released back into the sea via a turbine house from the reservoir, which is located above sea level.

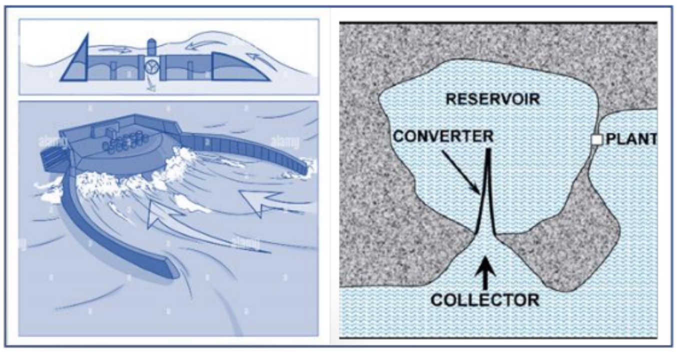

Figure 1. Wave converter Dragon type (left side) and Tapchan type (right side) [11]

2.2. Wave and Wave Transformation

Based on Laplace's equation for irrotational flow and boundary conditions on the seabed and the water's surface, the theory of airy waves is developed. Some of the wave parameters that propagate in the *x-axis* direction which are generally used in calculations as shown in Figure 2 are water depth (d), fluctuations in water level to still water level (x, t), which can be calculated by the equation $= \ a \cos\,(kx.t)$, where, a: amplitude, wave height ($H = 2a$), wavelength (L), Wave period (T), Wave propagation speed, $C = L/T$; wave number ($k = 2\pi/L$); wave frequency ($\sigma = 2\pi\ /T$), acceleration due to gravity ($g = 9.81\ m/s2$). The relationship of wave propagation speed with wavelength and depth is:

$$C = \frac{gT}{2\pi} tanh \frac{2nd}{L} \tag{1}$$

And the relationship wavelength (L) in the function of water depth (d) is:

$$L = \frac{gT^2}{2\pi} tanh \frac{2nd}{L} \tag{2}$$

where,

$$n = \frac{1}{2}\left(1 + \frac{2kd}{Sinh2kd}\right) \tag{3}$$

If a series of waves propagate towards the coast, then the wave will undergo a change in shape or transformation including the process of refraction, shoaling, diffraction, reflection, and breaking waves. The idea of equivalent deep-sea waves, or the height of deep-sea waves if refraction does not occur, is frequently used in wave transformation analysis. The use of the transformation wave aims to determine the height of the wave undergoing refraction, diffraction, and other transformations so that it is easier to

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estimate the transformation and deformation of the wave. The form provides the equivalent deep sea wave height.

$$H_o' = K' . K_r . H_o \quad (4)$$

where Ho' is the equivalent height of deep-sea waves, Ho is the height of deep-sea waves, K' is the diffraction coefficient, and Kr is the refraction coefficient.

A coastal structure will reflect some or all of the energy of an incoming wave. Waves will completely reflect off of the smooth, impermeable walls of vertical structures. The reflection coefficient (Kr), which is the product of the reflection wave height Hr and the incident wave height Hi, determines the extent to which a structure can reflect waves:

$$Kr = \frac{Hr}{Hi} \quad (5)$$

The modification brought on by shoaling is another wave of deformation. The Shoaling Coefficient, which is the proportion of deep-water wavelengths to beach wavelengths, can also be used to measure shoaling.

$$Ks = \sqrt{\frac{n_0 L_0}{nL}} \quad (6)$$

where the value of n changes to 1 in shallow waters and $n0$ = the depth factor in deep sea waters.

2.3. Wave Energy and Wave Power

Kinetic energy and potential energy of waves are the two types of wave energy. The orbital velocity of particles caused by wave motion generates kinetic energy. While the potential energy is caused by a wave's motion shifting the water's level. The components of potential energy and kinetic energy are the same for the small-amplitude wave theory if the wave energy is set relative to a stationary water surface and all waves propagate in the same direction. Consequently, one wavelength's total energy per unit wavelength is [12]:

$$Et = Ek + Ep = \frac{\rho g H^2 L}{8} \quad (7)$$

While the average energy per unit area is:

$$E = \frac{Et}{L} = \frac{\rho g H^2}{8} \quad (8)$$

Wave power (P) is the wave energy per unit time in the direction of wave propagation, where Ek is the kinetic energy per unit wavelength ($joules/m$), Ep is the potential energy per unit wavelength ($joules/m$), Et is the total energy per unit wavelength ($joules/m$), E is the average wave energy per unit area ($joules/m2$), H is the wave height (m), is the density of water ($kg/m3$), and g is the acceleration due to gravity (m).

$$P = \frac{nE}{T} \quad (9)$$

The available power in the reservoir is [13]:

$$D = Qh\rho g \quad (10)$$

Where h is the difference height between the water level in the reservoir and the sea surface.

2.4. Wave Energy Conservation

A wave that propagates enters a narrowed area, then its energy will be conserved at the 2 points under consideration. Figure 2 presents the conservation of wave energy in a narrowed channel.

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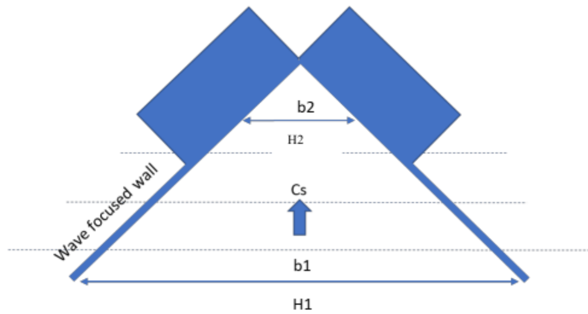

Figure 2. Conservation of wave energy on Focusing Wall

$$(EnC)_1 b_1 = (EnC)_2 b_2 \quad (11)$$

Then, the wave height $H2$ can be solved:

$$H_2 = H_1 K_s \sqrt{b_1/b_2} \quad (12)$$

Where, $C = L/T$ = Wave propagation velocity (m/s); Ks = Shoaling coefficient; $H1$ = wave height at point 1, while $H2$ = wave height at the point 2; $b1$ = width of the focused wall at the point 1, while $b2$ = width of the focused wall at the point 2.

3. Research Method

The study was carried out at the Faculty of Engineering, Hasanuddin University, Indonesia's Coastal & Environmental Engineering Laboratory. In a wave basin measuring 10 m by 15 m and having a depth of 1 m, experimental studies on 3D physical models are being conducted. Three different wave heights and periods (H & T), five different freeboard heights (Fb), and two different WCSP-DS models with and without wave energy-focusing collector walls (WFW) are simulated at three different elevations of the water level in relation to the vertical wall ($d/z = 0.857$; $d/z = 1$ & $d/z = 1.13$) as shown in Figure 3. The figure presents a layout physical simulation in a 3D wave basin 4.

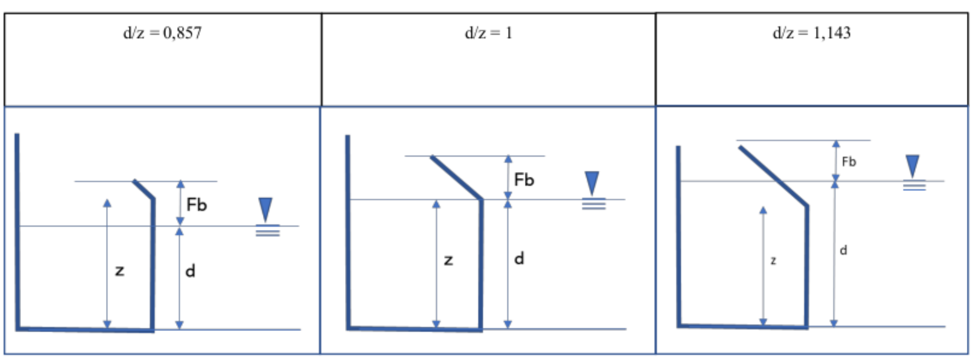

Figure 3. Three different types of water level elevation profiles in relation to a vertical wall

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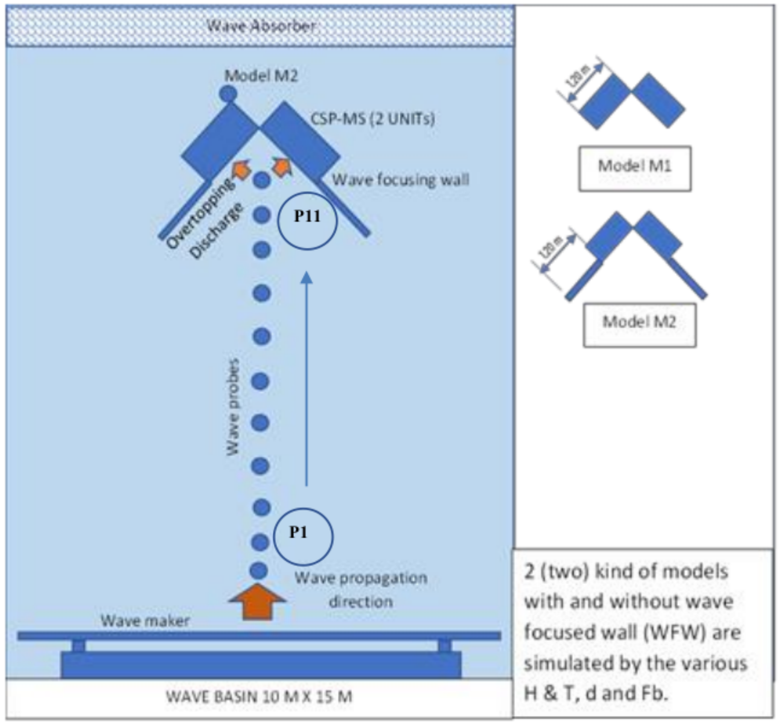

Figure 4. The layout of 3D physical simulation

From the wave generator to the WCSP-DS model, the positions of the probes P1 to P11 are listed in order. The wave generator device is set up in accordance with the simulation plan after the model is constructed and placed in the wave basin in accordance with the plan shown in Figure 4. Thereafter, the 11-piece calibration of the generator and wave height measuring probes is completed. The following step involves wave height simulation and data collection for all probes. Other variations are tried out by repeating the process.

4. Result and Discussion

In order to find data trends, relationships, or effects between parameters, the water level fluctuation recording data from the simulation results are then converted to wave height (H) on all probes (P1 - P11). A sample of the simulation parameter data and the recorded deformation wave height for the zigzag model without collector (M1) and with the collector (M2) are shown in Table 1.

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Table 1. Simulation parameter data for d/z =1.143 and T = 2 s in the M1 and M2 experiments

Model	Running Cycles	Water Depth	Freeboard		Height of Vertical Wall	Water Depth Relative	Period	Wave Length in Deep Water	Wave Length	Wave Amplitude	Running Time
	Code	d (m)	Rc Lab	Fb (m)	z (m)	d/z	T (dt)	Lo (m)	L (m)	a (cm)	Sekon (s)
M1	V11	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	4	180
	V12	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	5	180
	V13	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	6	180
	U11	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	4	180
	U12	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	5	180
	U13	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	6	180
	etc	....		....	....	....	....	....	....	....	....
M2	X11	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	4	180
	X12	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	5	180
	X13	0.4	40	0.35	0.35	1.142857	2.0	6.2400	3.8837	6	180
	W11	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	4	180
	W12	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	5	180
	W13	0.4	35	0.3	0.35	1.142857	2.0	6.2400	3.8837	6	180
	etc	....		....	....	....	....	....	....	....	....

Table 2. A part of recorded deformation wave height (Hdf) and overtopping unit discharge (q) for each simulation cycle at relative depth (d/z) = 1.143 and T = 2s

Model	Running Cycles	Wave Height Record at 11 Probes (m)											Overtopping Discharge Unit
	Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	q/1000 (m3)
M1	V11	0.073	0.073	0.068	0.114	0.123	0.112	0.117	0.105	0.096	0.051	0.152	0.000
	V12	0.094	0.094	0.095	0.156	0.145	0.141	0.134	0.141	0.127	0.060	0.183	0.000
	V13	0.113	0.113	0.121	0.188	0.178	0.179	0.155	0.168	0.159	0.080	0.194	0.000
	U11	0.073	0.073	0.077	0.122	0.134	0.119	0.135	0.120	0.111	0.057	0.161	0.000
	U12	0.097	0.097	0.106	0.169	0.161	0.157	0.146	0.151	0.140	0.065	0.187	0.000
	U13	0.128	0.128	0.128	0.207	0.201	0.192	0.168	0.189	0.181	0.088	0.215	0.026
	etc	etc	....		....	....	....	....	....	....	....	....	....
M2	X11	0.095	0.084	0.175	0.202	0.086	0.107	0.159	0.163	0.062	0.226	0.430	0.009
	X12	0.121	0.088	0.243	0.230	0.107	0.145	0.213	0.195	0.061	0.284	0.473	0.415
	X13	0.143	0.102	0.262	0.282	0.127	0.148	0.202	0.219	0.075	0.301	0.540	1.161
	W11	0.095	0.086	0.172	0.213	0.088	0.105	0.178	0.166	0.070	0.231	0.433	0.054
	W12	0.121	0.095	0.226	0.241	0.106	0.126	0.204	0.189	0.062	0.284	0.484	0.893
	W13	0.114	0.104	0.187	0.214	0.105	0.133	0.177	0.157	0.072	0.258	0.462	1.662
	etc	etc	....		....	....	....	....	....	....	....	....	....

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The relationship between several simulation parameters, such as relative depth (d/z), Freeboard height (Fb), overtopping unit discharge (q), and deformation wave height (Hdf), is then examined using all acquisition data, such as Table 2 above. From this recorded data, it can be seen that all simulation cycles resulted in an increase in the height of the deformation wave with the maximum height occurring at Probe 11 (at front of the model) (at front of the model).

4.1. Effect of Relative Depth (d/z)

The first analysis that needs to be performed compares the impact of the water level's vertical position on the WCSP's vertical wall height. Three vertical positions are examined for their effects: d/z = 1.143, which indicates that the water level is on an inclined upper wall; $d/z = 1$, which indicates that the water level is at the intersection of an inclined upper wall and an upright sub wall; and $d/z = 0.857$, which indicates that the water level is at a sub wall (upright wall). In Figure 5, the deformation wave profiles are compared for the three different water level positions in the model without and with WFW under the conditions of freeboard height (Fb), amplitude (a), both at wave period (T) $= 2.0\ s$, and at $T = 2.3\ s$.

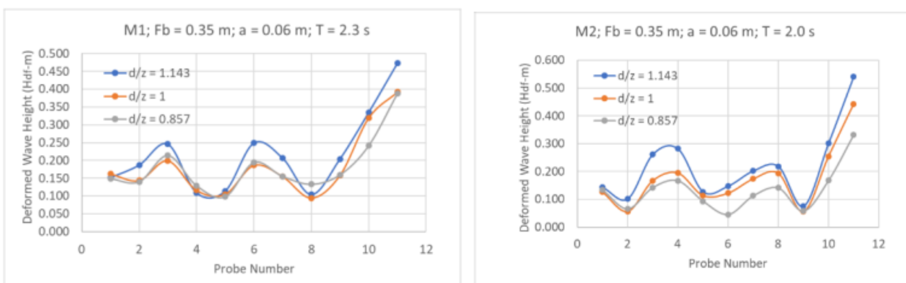

Figure 5. Comparison of three different face elevation positions' deformation wave profiles

Figure 5 shows that from Probe 1 to Probe 11, the wave height significantly increased for all deformation wave profile curves that occur in the M1 model, the model without WFW, as well as the M2 model with WFW. The three curves in both models demonstrate that $d/z = 1.143$ is the relative face elevation position that has the greatest impact on an increase in wave height. This indicates that the water level elevation is on the upper wall (inclined 45^{o} wall) or above a sub-wall (upright wall). Therefore, the d/z value will be discussed further.

4.2. Relationship of Freeboard Height (Fb), Overtopping Discharge (q), and Deformed Wave Height (Hdf)

The freeboard height is one of the key factors in the OWEC study (Fb). The overtopping discharge unit (q) that enters the reservoir is significantly influenced by the freeboard height, and q itself is significantly influenced by the deformation wave height (Hdf) formed. The deformation wave height (Hdf) is a significant variable in this study that affects the magnitude of the difference in water levels between the reservoir and the sea (h), which affects how much power the reservoir can produce. To increase the Hdf, engineering is carried out by placing the WCSP model box in a zig-zag manner and providing an additional structure that changes the collector wall to concentrate the wave energy. There is a triangular relationship that influences each other between the freeboard height (Fb), the overtopping unit discharge (q), and the deformation wave height (Hdf). Figure 6 and figure 7 present the relationship between the three parameters and their comparison in the M1 and M2 models.

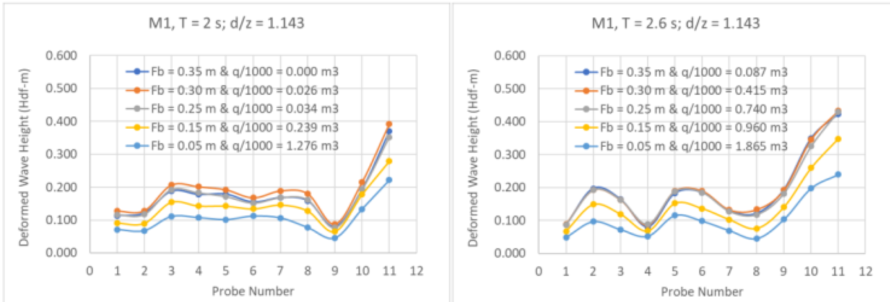

Figure 6. The relationship between Fb, q and Hdf at $d/z = 1.143$ and for $T = 2\ s$ & $T = 2.6\ s$ of M1 model (zigzag model without WFW)

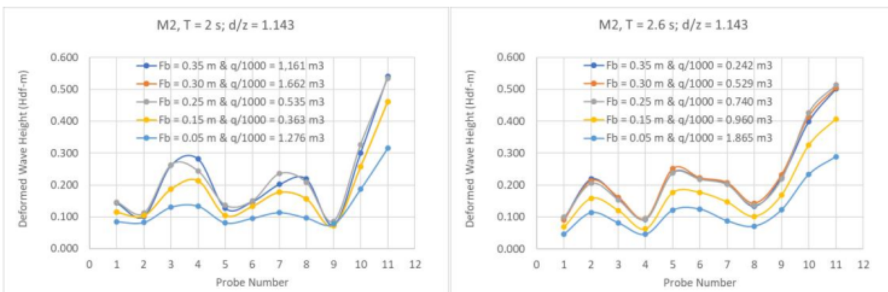

Figure 7. The relationship between Fb, q and Hdf at $d/z = 1.143$ and for $T = 2\ s$ & $T = 2.6\ s$ of M2 model (zigzag model with WFW)

Figure 6 and figure 7 show the wave transformation curve that occurs during propagation from point 1 (in the deep sea) to point 11 which is located in front of the WCSP-DS Model. The effect of the wave period (T) within the limits of the studied values has no significant effect on Hdf for both model conditions. The presence of an additional energy-focusing collector structure has a significant effect on the Hdf height, especially in front of the model (P11), where the Hdf achievement on M2 is greater than that of M1 for all Fb conditions. It can be seen that the larger the Fb, the larger the recorded Hdf, and the smaller the overtopping discharge (q) that is caught. This condition can also be explained that the greater the discharge (q) that flows into the reservoir due to the lower Fb, the smaller the Hdf that occurs. This can be understood in accordance with the theory that the Hdf height is formed by 3 mechanisms, namely energy concentration with the application of the law of energy conservation, the formation of standing waves due to reflection by walls with a height of Fb, and the shoaling process due to the slope of the seabed (Ks). This finding is also consistent with the research of Hatta M. P. et al. and Puspita A. I. D. et al. The value of Hdf decreases with increasing overtopping discharge as shown in the bottom 2 curves in Figure 6 and Figure 7. The top three curves tend to be high and close together because there is no or almost no overtopping discharge into the reservoir. These results indicate that there is an ideal combination of the height of Fb and the value of q which will give the best value to produce optimal electrical power.

4.3. Increase in Deformed Wave Height

Waves will change in height as they move from the deep sea to the shallow water along the coast. The amount of energy captured increases with increasing wave height. Figure 8 shows the wave steepness scale's (Hi/L) percentage increase in wave height from point 1 in the transition ocean to point 11 in front of the model.

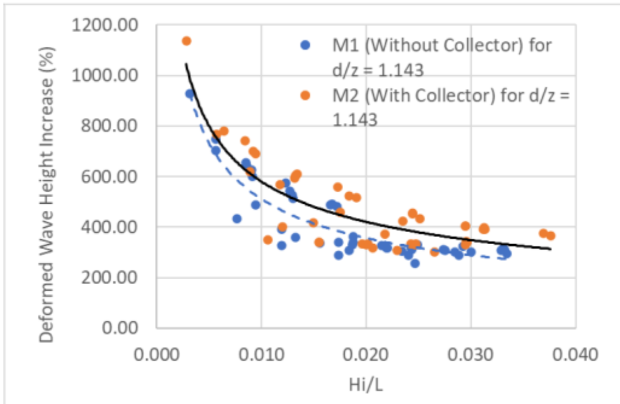

Figure 8. Relationship of increase in Hdf (%) with wave steepness (Hi/L) for Model M1 (without collector) and M2 (with collector) at relative depth $(d/z) = 1.143$

From Figure 8 it is clear that the wave steepness (Hi/L) is a significant factor in the rise in the deformed wave height (Hdf). This is because the greater the value of Hi/L, the greater the chance of the waves breaking on the walls of the structure causing the reflection of the waves to be small so that standing waves are not formed. This is also in accordance with what was also found by Puspita A. I. D et al. It can be seen that the higher the steepness of the Hi/L wave, the less the deformation wave height increases by percentage (Hdf). It is also seen that the WCSP model with a wave energy focusing collector (M2) gives a higher percentage value than M1 (without a collector). The Hdf height increase in the ranges of 300% to 900% on zigzag WCSP models without additional collectors, while the Hdf increase in the ranges of 350% to 110% for the models with additional collectors (M2) with a length equal to the length of the WCSP model. Based on the small difference between both models, then it can be recommended for the M1 type for suitable implementation in the field.

5. Conclusion

Following is a list of conclusions that can be drawn from the analysis's findings.

1. From the analysis of the relationship between relative water depth (d/z) and Hdf, the largest value is obtained at $d/z = 1.143$, or the position of the water level elevation is on a sloping wall above the WCSP-DS upright wall for both conditions of the model studied.
2. Obtained a triangular relationship that influences each other between the freeboard height (Fb), the overtopping unit discharge (q), and the deformation wave height (Hdf).
3. At a high Fb value, the overtopping discharge value becomes small, causing the Hdf value to also be high due to the formation of standing waves due to high reflection energy and vice versa.
4. The results show that there are ideal conditions for the combination of the height of Fb and the value of q which will give the best value to produce optimal electrical power according to Equation (10).
5. The percentage increase in Hdf height ranges from 300% to 900% on zigzag WCSP models without additional collectors and ranges from 350% to 1100% increases in models with additional collectors (M2) with a length equal to the length of the WCSP model.
6. With the small difference between both models, it can be considered to choose the M1 model for implementation in the field.

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