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Yu-Shu Kuo, Chi-Sheng Lin, Chih-Yin Chung, and Yu-Kai Wang

Key words: oscillating-water-column (OWC), wave loading, breakwater, wave energy.

ABSTRACT

Wave energy is one of the most potential marine energy resources in Taiwan, especially in the northeast and east coast of Taiwan. There are numerous existing wave energy devices. Among them, Oscillating Water Column (OWC) caisson breakwater is very suitable for the harbors in Taiwan. This multiple function structure can generate electric power and protect harbor. To evaluate the stability of OWC caisson breakwater, the loadings induced by wave acted on the OWC caisson breakwater are analyzed. Experiments of a small scale physical model of OWC caisson breakwater is presented in this study. The model is fixed in the wave flume and the wave pressures acting on the structure are recorded. It is found that wave pressure at oscillating water column caisson breakwaters is smaller than the wave pressure at vertical wall. The wave loadings calculated with the suggestion of Sainflou (1928) and Goda (1985) are compared with the test results. The applicability of the empirical formulas is also discussed. Under the selected wave condition, the Sainflou's formula overestimates the wave pressure acting on the OWC caisson breakwater. Goda's formula (1973) provides good estimation for the force estimation but tends to underestimate the momentum and could possibly result in structure overturning.

I. INTRODUCTION

Taiwan is an island country with limited natural energy sources. Renewable energy, such as capturing ocean wave energy, has high potential for meeting future demands. This study focuses on a wave power system that includes an oscillating water column (OWC) system and a caisson breakwater.

Evans (1978) developed a theory to describe the extraction efficiency of wave energy with consideration of system size, wave condition, and the wave direction. Evans (1982) further provided the relationship between the pressure distribution and extraction efficiency of wave energy under oscillating water column. Sarmento and Falcao (1985) compared the nonlinear air pressure effect inside the caisson under radiation flow condition with diffraction flow condition using both numerical and experiment verifications. Brendmo et al. (1996) mathematically described two oscillating water column systems and provided their application criteria. Clement (1997) studied the influence of the geometry of the wave front wall using a two-dimensional simulation model. Hong et al. (2005) studied the influence of water level, pressure, damping coefficient, and spring coefficient on the oscillating chamber using both numerical simulation and experiment. Yin et al. (2010) used the software FLUENT to simulate the pressure variation in the oscillating chamber. Tseng et al. (2000) studied the extraction efficiency of wave energy using a self-design oscillating column.

Takahashi et al. (1988) published a study on a modified oscillating water column system with caisson breakwater that provides improved wave absorption capability. In 1992, a field experiment at Sakata Port tested a breakwater and power generation system with a prototype breakwater (Takahashi et al., 1992). The result verified the applicability of Goda's formula (1973) for oscillating water column caisson breakwaters. Jayakumar (1994) indicated that the force loading for an oscillating water column caisson breakwater is smaller than the force loading for a traditionally vertical wall breakwater. Müller and Whittaker (1995) indicated that the wave pressure on the inner wall of the chamber is more important than the wave pressure on the wave front wall due to flow field turbulence and the reflectivity. Thiruvenkatasamy et al. (2005) studied the influence of system configuration on the force distribution in terms of structure sizing, density of the caisson, and the size of the vent. Liu et al. (2011) used the weight of the structure to resist the wave force and studied the stability

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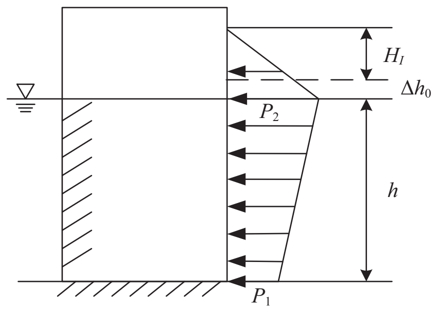

Fig. 1. The wave pressure distribution for overlapped waves (Sainflou, 1928).

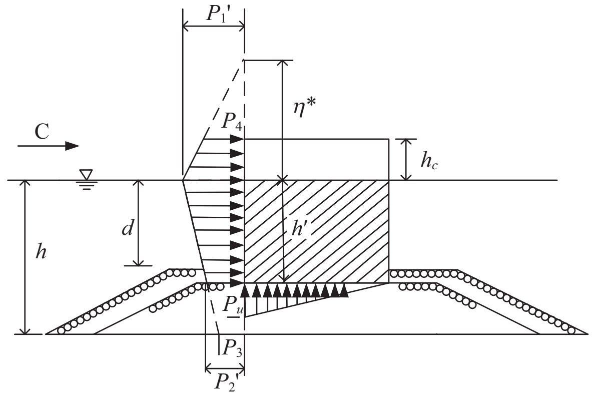

Fig. 2. The wave pressure distribution (Goda, 1973).

of the structure. Huang et al. (2010) applied a linear potential flow theory to calculate the horizontal wave force for an oscillating water column system with caisson breakwater and developed a reliability analysis method correspondingly. Torre-Encis et al. (2009) established a wave power generator using oscillating water column and caisson breakwaters at Biscay bay, Basque country, Spain. This power generator, the first in the world, has been operating since 2011 with a capacity of 300kW.

Current research has focused on the force loading distribution and ignored the sliding and overturning mechanisms of the structure, which are extremely critical for offshore structure stability. This study focuses on the wave loading distribution of oscillating water column caisson breakwaters under non-breaking wave forces and the stability analysis for the structure.

II. CALCULATION OF FORCE DISTRIBUTION ON VERTICAL WALL

Under non-breaking wave forces conditions, the wave pressure of the overlapped wave, superposition of incident wave and reflected wave, can be calculated using the following formulations.

1. Sainflou's Formula

With assumption of vertical wall without protection foundation, Sainflou (1928) indicated that the force distribution of the overlapped wave can be shown as Fig. 1.

$$\Delta h_0 = \frac{\pi H_I^{\,2}}{L} \coth kh \tag{1}$$

$$P_1 = \frac{\rho g H_I}{\cosh kh} \tag{2}$$

$$P_2 = \left(P_1 + \rho g h\right) \frac{H_I + \Delta h_0}{h + H_I + \Delta h_0} \tag{3}$$

where P_1 is the wave pressure at the bottom of the breakwater, P_2 is the wave pressure at the water surface, k is the wave number, h is the water depth and Δh_0 is the lifted distance for the mean water level. The Sainflou's formula is applicable for relative depth, h/L_0, between 0.1 and 0.15 where L_0 is the wavelength. The calculated value is overestimated if the relative depth is larger than 0.15. Otherwise, it is underestimated.

2. Miche-Rundgren's Forumla

Rundgren (1958) applied Miche's high-order theory to modify the Sainflou's formula, and obtained

$$\Delta h_0 = \frac{\pi}{4L}\left(1 + K_R\right)^2 H_I^{\,2} \coth kh \tag{4}$$

$$P_1 = \left(\frac{1 + K_R}{2}\right) \frac{\rho g H_I}{\cosh kh} \tag{5}$$

$$P_2 = \left(P_1 + \rho g h\right) \frac{\left[\left(1 + K_R/2\right) H_I\right] + \Delta h_0}{h + \left[\left(1 + K_R/2\right) H_I\right] + \Delta h_0} \tag{6}$$

where P_1 is the water pressure at the bed, P_2 is the wave pressure of the mean water level, H_I is the incident wave height and K_R is the reflection rate which is the ratio of the reflected wave height to the incident wave height.

3. Goda's Formula

Based on experiment, Goda provided a formula to calculate the wave pressure with the application range from overlapped wave to breaking wave (Goda, 1973). The design wave is the significant wave of the irregular waves. Fig. 2 shows the wave pressure distribution.

(1) The distance from mean water level to where the wave pressure is zero is defined as

$$\eta^* = 0.75\left(1 + \cos\beta\right) H_{max} \tag{7}$$

where β is the angle between vertical line of breakwater and wave direction, H_{max} is the design wave height which can be calculated using $H_{max} = 1.8H_{1/3}$ and $H_{1/3}$ is the significant wave height.

(2) Pressure intensity

Wave pressure at mean water level is

$$P_1' = \frac{1}{2}(1+\cos\beta)\left(\alpha_1 + \alpha_2 \cos^2\beta\right)\rho g H_{max} \tag{8}$$

Wave pressures at foot-protection block are

$$P_2' = \frac{P_1'}{\cosh kh} \tag{9}$$

$$P_3 = \alpha_3 P_1' \tag{10}$$

$$\alpha_1 = 0.6 + \frac{1}{2}\left[\frac{2Kh}{\sinh 2kh}\right]^2 \tag{11}$$

$$\alpha_2 = \min\left\{\frac{h_{b1}-d}{3h_{b1}}\left(\frac{H_{max}}{d}\right)^2, \frac{2d}{H_{max}}\right\} \tag{12}$$

$$\alpha_3 = 1 - \frac{h'}{h}\left[1 - \frac{1}{\cosh kh}\right] \tag{13}$$

where h is the water depth in front of the breakwater, h_{b1} is the water depth at 5 times of $H_{1/3}$ in front of the breakwater, d is the depth above the armor layer of the rubble foundation and h' is the distance from the design water level to the bottom of the upright section.

III. EXPERIMENT

1. Model Scale

The experiment is verified by two scales: 1:40 and 1:60. Since gravity and the inertia force are two major factors, the Froude number is selected for dynamic similarity that is expressed as:

$$\frac{V_m}{\sqrt{gl_m}} = \frac{V_p}{\sqrt{gl_p}} \tag{14}$$

where the subscription m is the indicator for model experiment and p refers to the prototype's parameters. The scale factor λ is the ratio of prototype to the model. The transformation of physical parameters via the dynamic similarity can be shown as followings:

$$\text{length scale: } \frac{l_m}{l_p} = \frac{1}{\lambda} \tag{15}$$

Table 1. The geometry size of oscillating water column caisson breakwaters.

	Full size	Experiment size
Length of the caisson S (m)	20	0.5
Opening width of front wall b (m)	10	0.25
Outside length of the chamber l_c (m)	10	0.25
Diameter of the vent D (m)	2.3	0.057
The distance between the breakwater top and the mean water level h_c (m)	10	0.25
The distance between the mean water level and the opening top h_1 (m)	2.25	0.056
Spacer thickness t (m)	0.4	0.01

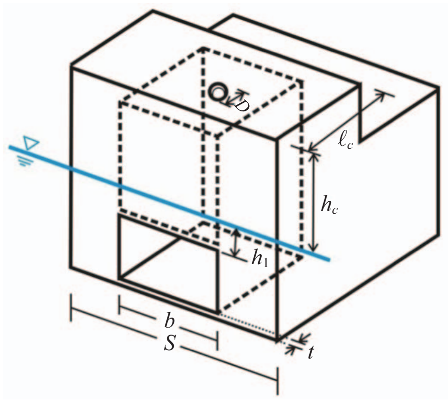

Fig. 3. The geometry of oscillating water column caisson breakwaters.

$$\text{period scale: } \frac{T_m}{T_p} = \frac{1}{\sqrt{\lambda}} \tag{16}$$

$$\text{pressure scale: } \frac{P_m}{P_p} = \frac{1}{\lambda} \tag{17}$$

2. Channel Experiment

The channel experiment's mold is constructed of acrylic to simulate a single caisson breakwater in the oscillating water column system shown in Fig. 3. The geometric parameters of the mold are listed in Table 1, where the value b/S and diameter of the upper pore, D, are referred to Thiruvenkatasamy's study in 2005. Fig. 4 is a schematic diagram of the experimental configuration which is placed in a sink that is 25 m long, 0.5 m wide, and 0.6 m high. The wave maker used is a Piston type that can create both regular and irregular waves at a water depth of $h = 0.25$ m. The dotted lines area in the figure shows the position of the mold, fixed by a truss, to find the wave pressure distribution without sliding. There are four wave gauges in the experiment: the first wave gauge measures the incident wave parameters, the second and the third wave gauges assess the water levels at the 0.01 m position ahead of the center line of wave wall with and without opening, and the

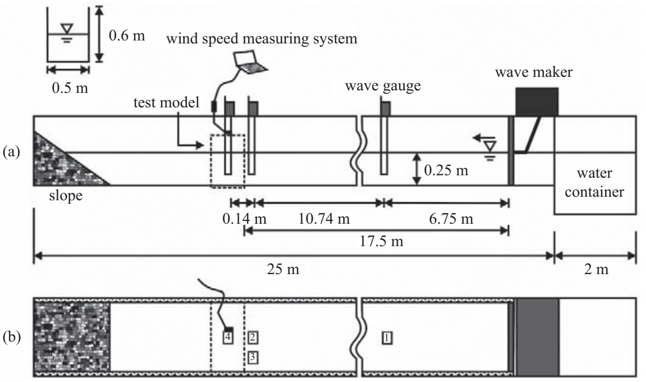

Fig. 4. Configuration of the experiment: (a) the lateral view and (b) the top view.

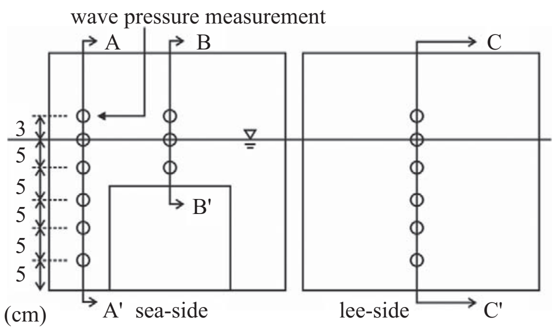

Fig. 5. The configuration of the pressure meters.

fourth wave gauge estimates the water level at the center of the chamber.

The configuration of wave pressure measurement is shown in Fig. 5, where on the sea-side, there are six and three wave pressure holes at the section AA' and BB', respectively. While on the lee-side, there are six wave pressure holes at the section CC' that is used to measure the pressure inside the chamber. The instruments are calibrated based on standard calibration procedures. The experimental data are recorded to the computer automatically with a 100 Hz data acquisition rate. In this experiment, we assume that the compression faces with the same properties have identical wave pressure distributions allowing the area integrals to be carried out to get the total force acting on the structure.

3. Wave Condition

According to Yan and She (2006), the east and northeast coast of Taiwan have high potential of wave energy. This characteristic may indicate that the breakwaters located in Hwalian coast could be a possible site for exploitation of the wave energy. In this study, the experiments are designed to represent the water depth and wave condition of Hwalian. Due to the limitation of the wave machine, period are set between 0.6 and 1.6 sec with wave heights at 0.02, 0.04, or 0.06 m. Table 2 shows the dimensionless wave sharpness

Table 2. The wave condition for the experiments. (Water depth h = 0.25 m).

Period T (sec)	Wave length L (m)	Relative water depth h/L	Wave height H (m)	Wave sharpness H/L	Relative wave height H/h	kh
0.6	0.558	0.448	0.02	0.036	0.08	2.813
	0.582	0.429	0.04	0.072	0.16	2.697
	0.608	0.411	0.06	0.108	0.24	2.584
0.8	0.933	0.268	0.02	0.022	0.08	1.683
	0.933	0.268	0.04	0.044	0.16	1.683
	0.958	0.261	0.06	0.066	0.24	1.639
1.0	1.3	0.192	0.02	0.015	0.08	1.205
			0.04	0.031	0.16	
			0.06	0.046	0.24	
1.2	1.66	0.151	0.02	0.012	0.08	0.946
			0.04	0.024	0.16	
			0.06	0.036	0.24	
1.4	2	0.125	0.02	0.01	0.08	0.784
			0.04	0.02	0.16	
			0.06	0.03	0.24	
1.6	2.684	0.093	0.02	0.009	0.08	0.671
			0.04	0.018	0.16	
			0.06	0.026	0.24	

(H/L), relative wave height (H/h), and wave dimensionless parameter (kh).

IV. RESULTS

1. Applicability of the Empirical Formula

The results are compared with the empirical formulas provided by Sainflou (1928) and Goda (1973). The applicability of the empirical formulas is also discussed. Fig. 6 shows that the experiment results fit the Goda's formula best for shallow water waves which are more representative of our study. The Sainflou's formula overestimates the wave pressure in these regions. In the subsequent sections, the Goda's formula is applied for this study.

2. The Wave Pressure at Different Sections

Figs. 7 to 9 show the maximum wave pressure at sections AA', BB', and CC' for the vertical wall without holes. Fig. 7 show that, if relative water depth (h/L) is between 0.261 and 0.448, the maximum wave pressure occurs when the period is 0.6 sec and 0.8 sec for sections AA' and BB', respectively. No obvious pressure reduction is observed at the mean water level. Under the same period, the wave pressure reduction is directly related to the wave height. Large wave height usually results in high pressure reduction. With the period of 0.6 sec or 1.6 sec, the wave pressure distribution at the section CC' in the chamber is smaller than the wave pressure at the vertical wall. This result indicates that the wave pressure in the chamber is smaller than the incident wave pressure. When the period is

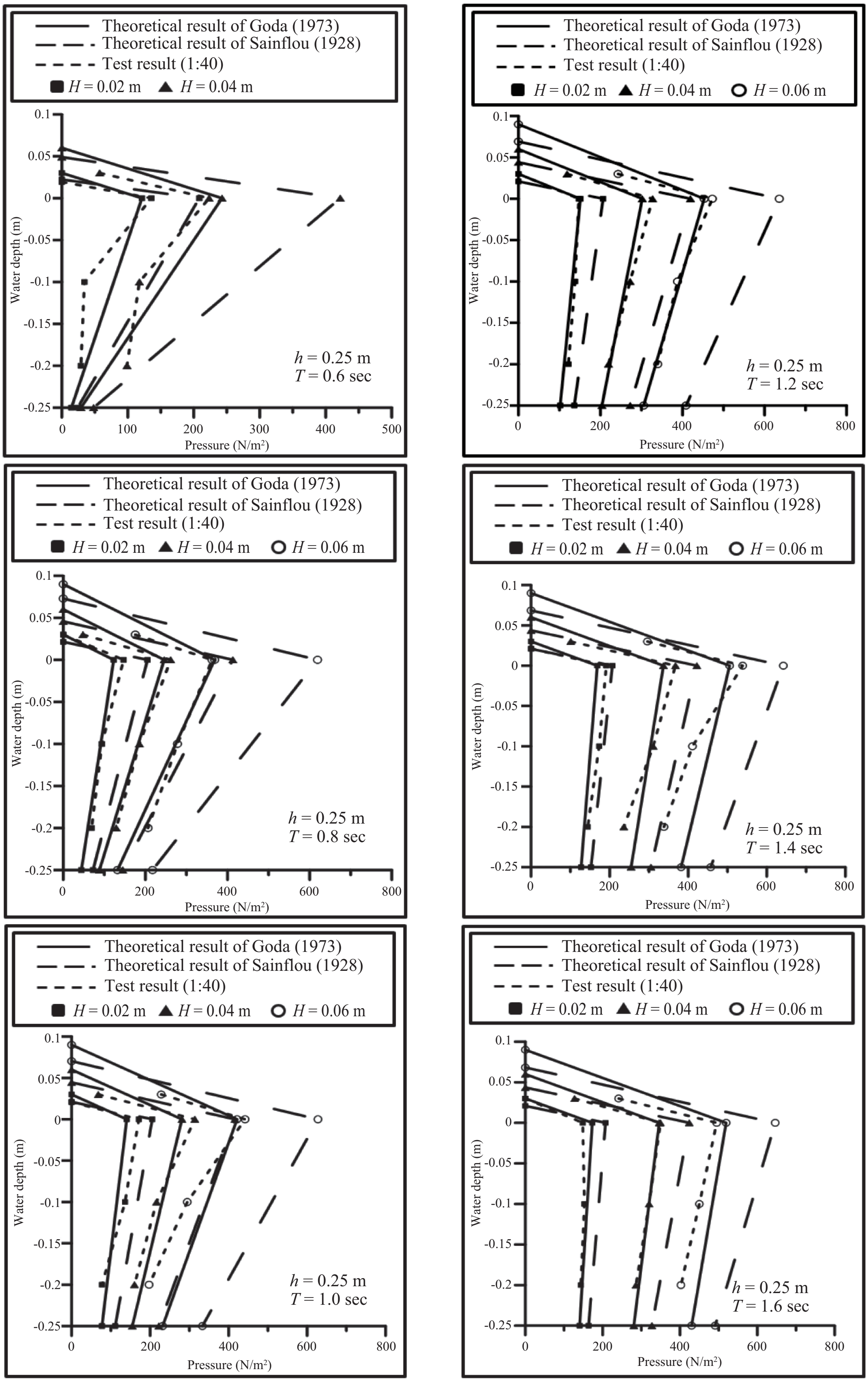

Fig. 6. Comparison along experimental results of vertical wall without opening, Goda formula, and Sainflou formula.

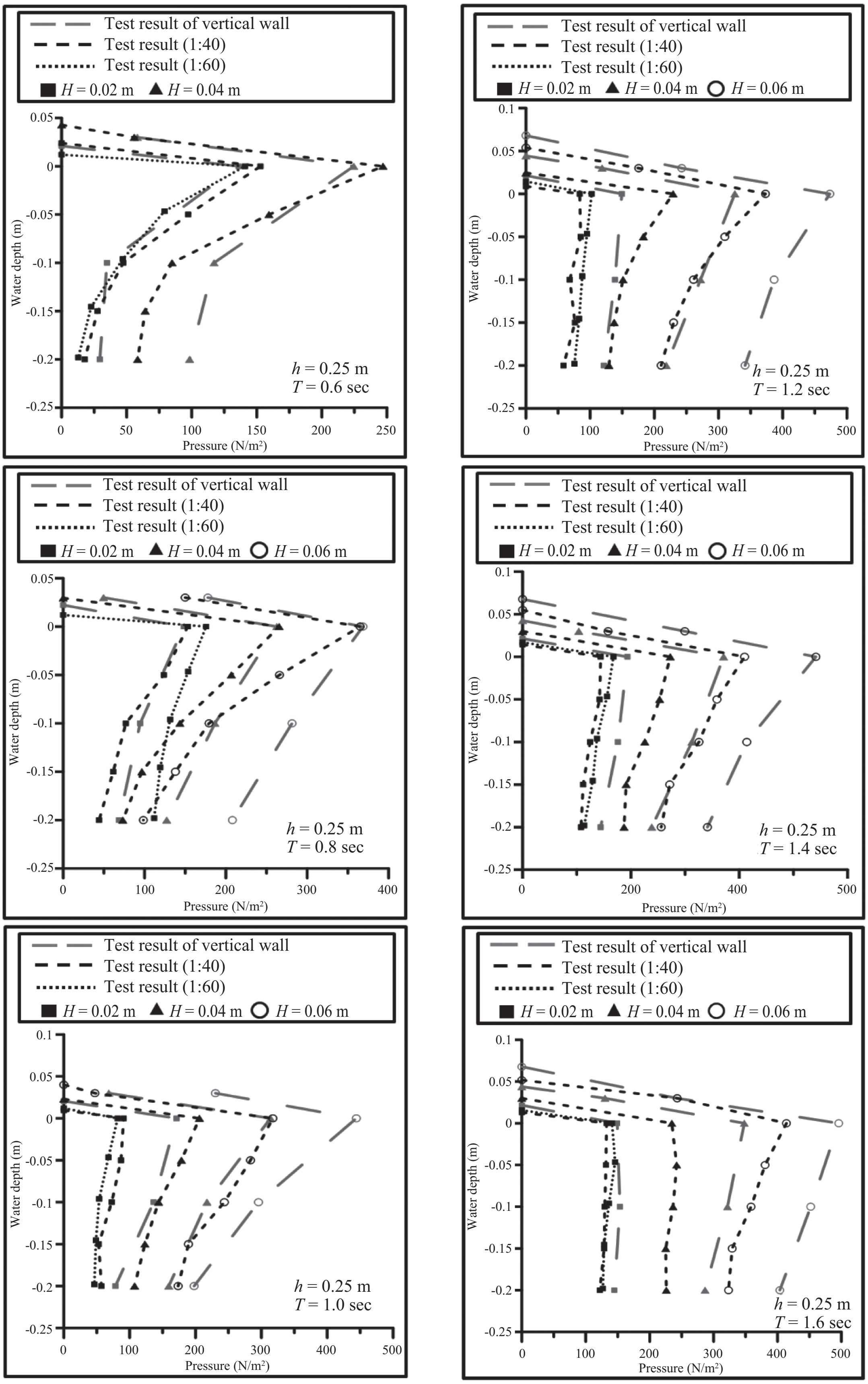

Fig. 7. Comparison of wave pressure between vertical wall and section AA'.

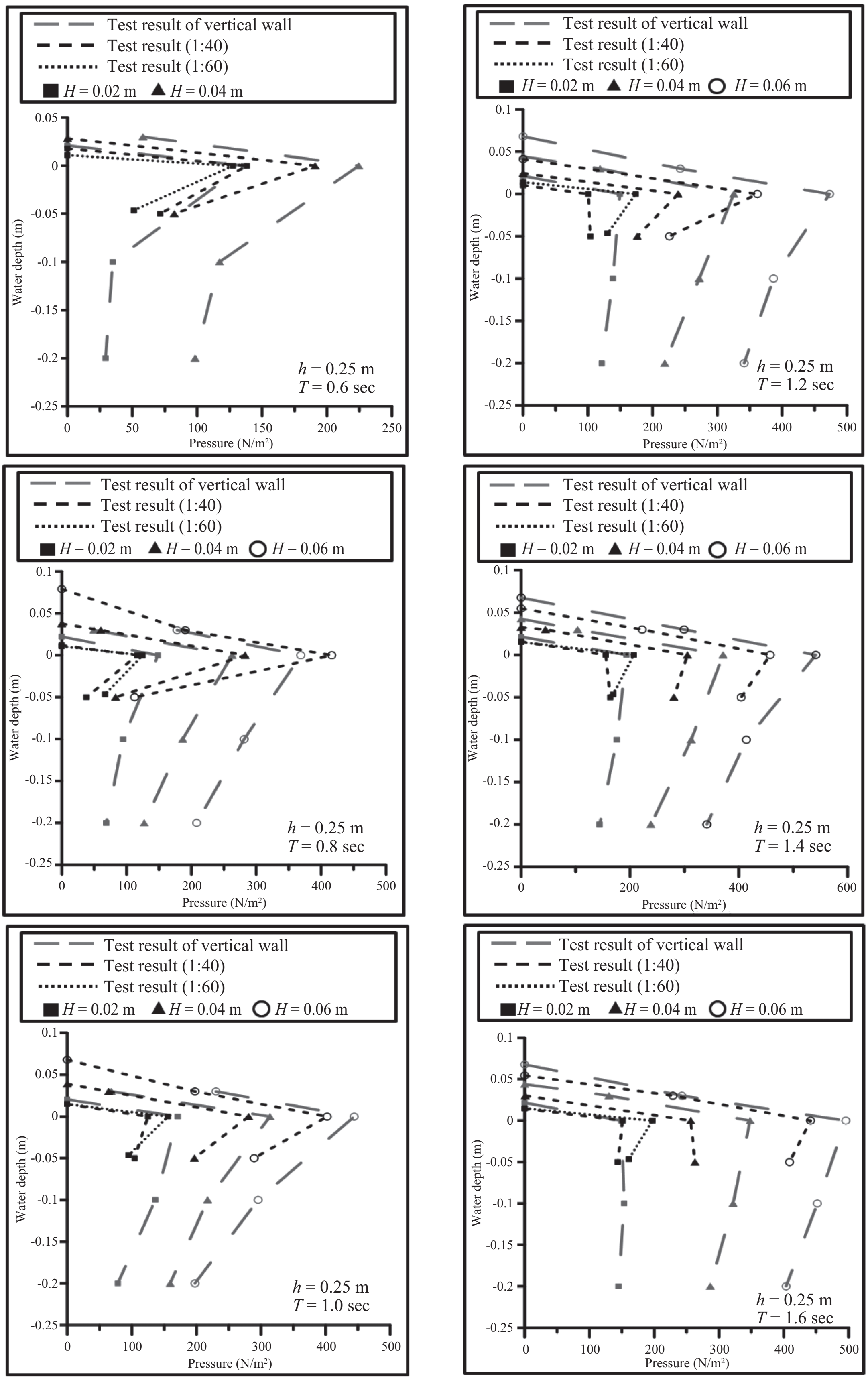

Fig. 8. Comparison of wave pressure between vertical wall and section BB'.

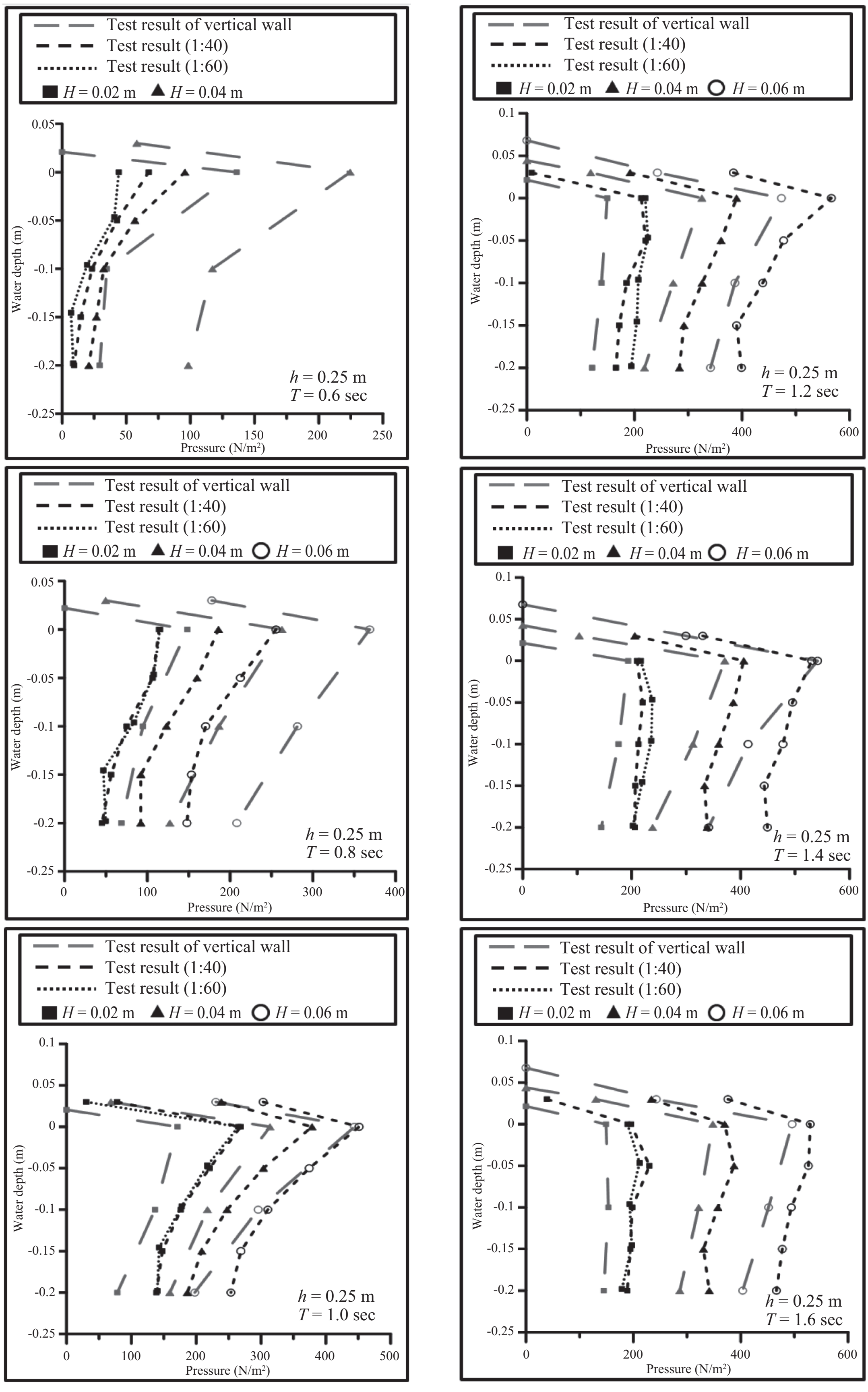

Fig. 9. Comparison of wave pressure between vertical wall and section CC'.

Fig. 10. Breaking wave in the oscillating water column caisson breakwater (period: 1.0 sec, wave height: 0.06 m).

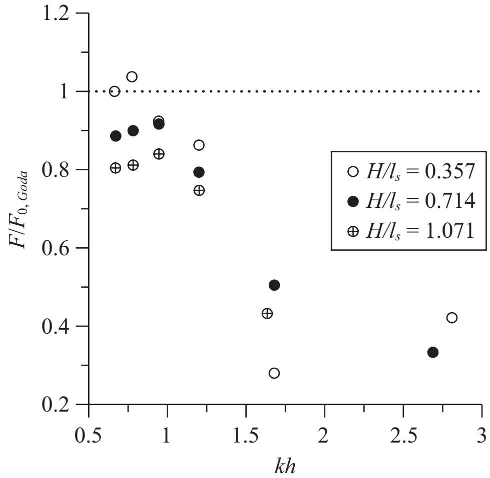

Fig. 11. Maximum force for experimental results and the estimation of Goda formula.

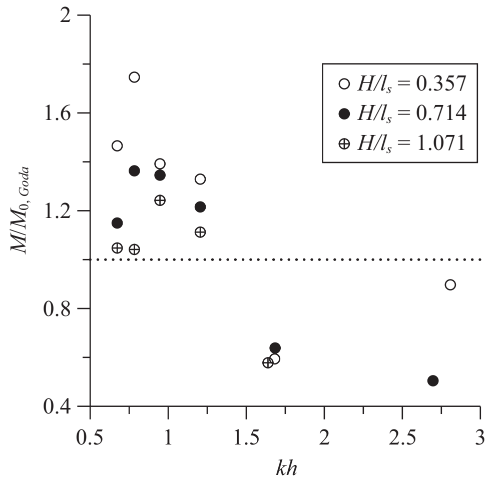

Fig. 12. Maximum momentum for experimental results and the estimation of Goda formula.

larger than 1 sec, the wave pressure in the chamber is larger than the incident wave pressure, and the breaking wave can be observed in the chamber (Fig. 10).

3. Maximum Force and Momentum for the OWC Caisson Breakwaters

Figs. 11 and 12 show the relationship between the value of *kh* and force ratio ($F/F_{0,Goda}$) and the moment ratio ($M/M_{0,Goda}$), respectively. Assuming the compression faces with the same geometries with section AA' and BB' have identical wave pressure distributions, the force per unit length of the caisson can be found from the sum of the areas of the pressure distributions. After determining the location of the resultant force, *F*, measured from the bottom of the caisson, the overturning moment *M* on the caisson can be calculated. Note that the force ratio and the moment ratio are expressed by the ratio of experiment result to the result obtained from Goda's formula. $F_{0,Goda}$ and $M_{0,Goda}$ are the calculated force and moment for wave pressure distributed at vertical wall without holes.

As shown in Fig. 11, Goda formula provides good estimation for the force estimation. The force ratio is smaller than 0.6 when *kh* is larger than 1.6 and the force ratio is between 0.7 and 1.1 when *kh* is smaller than 1.6. As shown in Fig. 12, the value of the momentum ratio is between 1 and 1.8, which indicates that Goda's formula tends to underestimate the momentum. This underestimation could result in a structure overturning.

V. CONCLUSION

This study focuses on the wave power using oscillating water column caisson breakwaters considering the wave conditions which can properly reflect the potential locations in Taiwan. The model scale of 1:40 and 1:60 are studied. The experiment results show the followings:

(1) The wave pressure at oscillating water column caisson breakwaters is smaller than the wave pressure at vertical wall. The wave pressure reduction increases with the increasing incident wave height *H* or decreasing relative water depth *h/L*, especially for value of *h/L* being 1/5 or smaller.

(2) Under different wave conditions, the wave pressure distribution has different characteristics. The wave energy is transferred via the movement of water particles. For shallow water conditions, the relative water depth *h/L* is smaller than 1/20, the energy is transferred across the entire section of the water depth or the water particles are fully moved on this section. For deep water conditions, the relative water depth *h/L* is larger than 1/2, the water particle movement is very small under certain depth of water depth or no energy transfer deeper than this water depth. For the water depth between these two conditions, the results from this study demonstrate that when the relative water depth is small the mechanism tends to show

the characteristic of shallow water condition.

(3) Goda's formula provides good estimation for the force estimation, but tends to underestimate the momentum and could possibly result in structure overturning.

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REFERENCES

Brendmo, A., J. Falnes and P. M. Lillebekken (1996). Linear modeling of oscillating water column including viscous loss. Applied Ocean Research 18, 65-75.

Clement, A. H. (1997). Dynamic nonlinear response of OWC wave energy device. International Journal of Offshore Polar Engineering 7(2), 154-159.

Evans, D. V. (1978). The oscillating water column wave-energy device. IMA Journal of Applied Mathematics 22, 423-433.

Evans, D. V. (1982). Wave-power absorption by system of oscillation surface pressure distribution. Journal of Fluid Mechanism 114, 481-499.

Goda, Y. (1973). A new method of wave pressure calculation for the design of composite breakwaters. Proceeding of the Port and Harbour Research Institute, Ministry of Transport, Nagase, Yokosuka, Japan, 41-69.

Goda Y. (1985). Random Seas and Maritime Structures, Tokyo.

Hong, S. W., D. C. Hong, S. Y. Hong, J. H. Kim, H. S. Choi and J. M. Lew (2005). Comparison of numerical dynamic pressure inside a pneumatic chamber of an OWC device with measured dynamic pressure by model experiments. Proceeding of The 15th International Offshore and Polar Engineering Conference, Seoul, South Korea, 542-548.

Huang, Y., H. Shi, D. Liu and Z. Liu (2010). Study on the breakwater caisson as oscillating water column facility. Journal of Ocean University of China 9, 244-250.

Jayakumar, V. S. (1994). Wave force on oscillating water column type wave energy caisson: an experiment study. Ph.D. Thesis, Department of Ocean Engineering, Indian Institute of Technology Madras, India.

Liu, Y., H. Shi, Z. Liu and Z. Ma (2011). Experiment study on a new designed OWC caisson breakwater. Proceedings of the 2011 Asia-Pacific Power and Energy Engineering Conference, Wuhan, China, 1-5.

Müller, G. and T. J. T. Whittaker (1995). Visualization of flow conditions inside a shoreline wave power-station. Ocean Engineering 22(6), 629-641.

Rundgren, L. (1958). Water wave forces. In: Bulletin 54, published by Royal Institute of Technology, Division of Hydraulics, Stockholm, Sweden.

Sainflou, M. (1928). Essai sur les Digues Maritimes Verticales. (Test on vertical sea dikes) Annales des Ponts et Chaussees 98, 5-48. (in French)

Sarmento, A. J. N. A. and A. F. O. Falcao (1985). Wave generation by an oscillating surface pressure and its application in wave energy extraction. Journal of Fluid Mechanics 150, 467-485.

Takahashi, S., T. Adachi and S. Tanaka (1988) Stability and function of improved-type wave power extracting caisson breakwater-A study on development of wave power. In: Report of the Port and Harbour Research Institute, Ministry of Transport, Yokosuka, Japan, 27(2), 23-58. (in Japanese)

Takahashi, S., T. Adachi and S. Tanaka (1992) Field experiment of a wave power extracting caisson breakwater. In: Report of the Port and Harbour Research Institute, Ministry of Transport, Yokosuka, Japan, 32(2), 21-54. (in Japanese)

Thiruvenkatasamy, K., S. Neelamani and M. Sato (2005). Nonbreaking wave forces on multiresonant oscillating water column wave power caisson breakwater. Journal of Waterway, Port, Coastal, and Ocean Engineering, 131(2), 77-84.

Torre-Enciso, Y., I. Ortubia, L. I. López de Aguileta and J. Marqués (2009). Mutriku wave power plant: from the thinking out to the reality. Proceeding of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 319-329.

Tseng, R. S., R. H. Wu and C. C. Huang (2000). Model study of a shoreline wave-power system. Ocean Engineering 27, 801-821.

Yan, Z. W. and W. Y. She (2006). Development of Numerical Techniques for Estimating Ocean Energy Distribution and Assessment of Exploitation. Bureau of Energy, Ministry of Economic Affairs, R.O.C. (In Chinese)

Yin, Z., H. Shi and X. Cao (2010). Numerical simulation of water and air flow in oscillating water column air chamber. Proceeding of the 20th International Offshore and Polar Engineering Conference, Beijing, China, 796-801.