ASEAN Engineering Journal

Full Paper

CONCEPTUAL DESIGN OF A RESEARCH WAVE FLUME IN INSTITUTE OF CIVIL ENGINEERING (ICE), UP DILIMAN

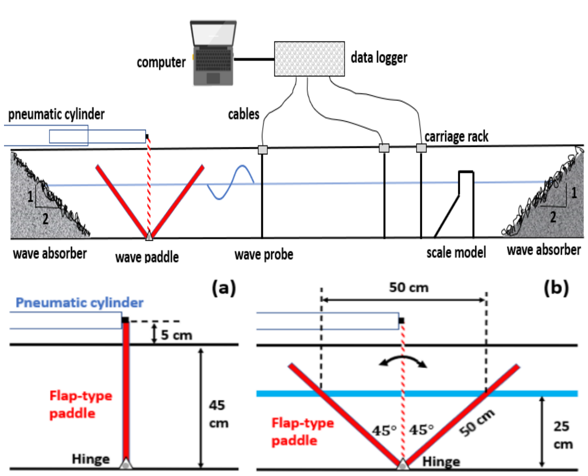
Dominic M. Bautista[a,b]*, Marjorie T. David[b], Ronaldyn E. Dabu[b], Georgia B. Asistin[b], Eric C. Cruz[a,b], Roberto S. Soriano[a,b]

[a]Institute of Civil Engineering, College of Engineering, University of the Philippines-Diliman, Quezon City, 1101, Philippines
[b]National Hydraulic Research Center, National Engineering Center, University of the Philippines-Diliman, Quezon City, 1101, Philippines

Article history
Received
13 August 2024
Received in revised form
08 March 2025
Accepted
19 March 2025
Published online
30 November 2025

*Corresponding author
dmbautista2@up.edu.ph

Graphical abstract



Abstract

One of the only two testing facilities in the Philippines that could supplement coastal engineering research is a 9-m long by 60-cm wide by 45-cm deep wave flume that uses a top-hinged, paddle-type wave generator powered by a rotating motor. It will be retrofitted by replacing the wave generator and extending it to allow longer waves to propagate. In this paper, we designed the new wave generator utilizing planar wavemaker and linear wave theories. We determined the maximum properties of the waves that can be generated given the physical limitations of the flume. The final design of the wave flume includes its extension to 22-meter length and a bottom-hinged, flap-type wave generator powered by a pneumatic cylinder attached to the top of a 0.5-meter length paddle. A maximum stroke of 0.5 meter at 25-cm deep still water level was set. Theoretically, it can generate model waves with heights up to 12.8 cm and period of 2.1 seconds. This new wave flume could jumpstart physical modelling studies in the country and be used by other local universities as basis in constructing their own wave flume for instruction and research.

Keywords: wave generator design, wave flume, physical model testing, planar wavemaker theory, linear wave theory

1.0 INTRODUCTION

The Philippines is an archipelagic country in Southeast Asia, with coastlines that are irregular with numerous bays, gulfs, and islets. With a coastline length of 36,289 km, about 60 percent of Philippine municipalities and cities are coastal, with 10 of the largest cities located along the coast. These coastal cities and municipalities are inhabited by about 60 percent of the total population [1]. The Philippines' location in the Western North Pacific makes it highly exposed to tropical cyclone systems. About eight tropical cyclones make landfall in the country every year making storm surges and intense waves a common natural coastal hazard [2]. The high exposure of coastal communities of the country, together with the presence of severe coastal hazards such as storm surges and coastal erosion render high risks that must be mitigated necessitating extensive coastal engineering research in the country. In the past decades, coastal engineering research in the Philippines has been focused on numerical simulations and empirical methods in characterizing the processes within the coastal environment. Numerical models, such as Delft3D and ADCIRC, have been applied in numerous local research to study tides [3], waves [4], sediment dynamics [4,5], and storm surge [6]. Similarly, empirical analysis based on field data have been utilized in describing tidal hydrodynamics [7], coastal morphology [8,9], and storm surge [10].

Experimental techniques employed in coastal engineering are aimed primarily at replicating real-world conditions within a highly controlled environment. This allows for the investigation of different complex processes such as wave breaking and wave overtopping, among others. Unlike numerical models, which are constrained by the oversimplifications defining mathematical equations, physical models can accurately replicate specific testing conditions while preserving uniform properties (except geometric dimensions) providing more flexibility in analysis [11]. In the early 1990s, 54% of research papers on coastal engineering utilized data from laboratory testing. This number has been dropping continuously as technological advancements in numerical modeling provides more cost-effective techniques of analysis [12]. Despite this, physical modeling remains relevant as it provides critical validation for numerical models and offers visual insights that cannot be captured through numerical simulations alone. This includes assessment of effectiveness of coastal structures such as breakwaters, revetments, and seawalls, as each of them possesses unique characteristics, necessitating validation of the proposed designs through physical testing [13].

In the Southeast Asian region, advancement in physical model testing has proliferated in the past decades. For instance, the Centre for River and Coastal Engineering in Malaysia houses a 20-m long x 5.3-m wide x 1-m deep wave basin and 18-m long x 0.7-m wide x 0.9-m deep wave flume that have been used extensively in various coastal engineering research [14]. In Vietnam, the Southern Institute of Water Resources Research River and Marine Hydrodynamic Laboratory houses a 35-m long x 1.2-m wide x 1.5-m deep wave flume and a 35-m long x 18-m wide x 1.1 m deep wave basin that were used in studies related to breakwater design [15]. In Indonesia, the Tsunami and Disaster Mitigation Research Center has a 60-m long x 2.5-m wide x 1.7-m deep wave flume used in studying waves and hydrodynamics under tsunami conditions [16]. In Thailand, the Asian Institute of Technology houses two wave flumes, one 40-m long x 0.45-m wide x 0.7-m deep and another 20-m long x 0.6-m wide x 0.6-m deep, and a wave basin that is 8-m wide and 10-m long [17]. Other coastal engineering testing laboratories are found in Universiti Teknologi PETRONAS in Malaysia, Thuyloi University in Vietnam, University of Hasanuddin in Indonesia, and Prince of Songkla University in Thailand. In the Philippines, the Coastal Engineering Research and Development Center was launched in Mariano Marcos State University last November 23, 2021. The center will spearhead the development of technologies and innovations to mitigate and manage coastal disasters and risks in the Philippines [18]. Included in the projects of the center is a wave testing facility that was inaugurated last February 3, 2025.

Despite the need for intensive coastal engineering research, the Philippines lags behind our Southeast Asian neighbors. As preliminary research in physical modelling of coastal systems in the country, the main objective of this study is to design the wave flume that will be retrofitted in the new Institute of Civil Engineering Coastal Laboratory. The retrofitted flume will be used to study wave overtopping and reflection on coastal structures. Technical aspects of the wave generator design are discussed thoroughly in this manuscript. This will guide interested local universities in selecting the appropriate wave flume that will fit their research and instruction agenda on the field of coastal engineering. Finally, this facility will jumpstart future physical modelling activities that will supplement and advance coastal engineering research in the country.

2.0 METHODOLOGY

2.1 Existing Wave Flume

The existing wave flume facility is housed in the National Hydraulic Research Center (NHRC) of the College of Engineering in University of the Philippines Diliman. It is a 9-m long, recirculating-type towing tank and tilting flume used to demonstrate open channel processes and wave phenomenon. The cross-section of the flume measures 45 cm high and 60 cm wide. The clear side panel is made of glass supported by a steel frame. Figure 1 shows images of the profile of the wave flume at the inlet and outlet. Due to limitations of the wavemaker to be installed, it is anticipated that the existing length of the flume will not facilitate an experimental time window that is convenient for the wave flume users. Hence it is proposed to extend the length of the flume. It does not include instruments and devices to measure pertinent data such as wave height and period. Previously, experiments conducted using the existing flume used improvised methods to measure wave properties. The propagation of the waves in the flume would be video recorded, and the period would be determined by measuring the time it takes for succeeding wave crest to cross a specific marked section of the flume, while the wave height is measured using rulers attached to the sides of the clear panel. In the proposed retrofit, relevant instruments such as wave probes connected to a data logging system are intended to be installed in the flume.

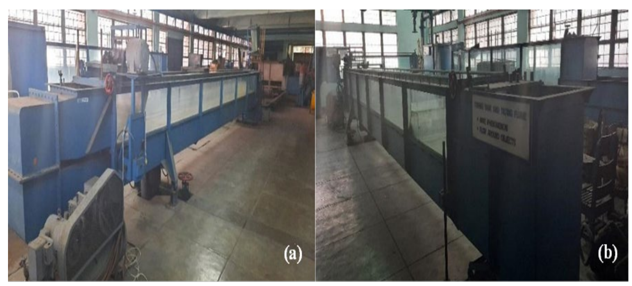


Figure 1 The existing wave flume: (a) inlet and wavemaker side and (b) outlet to sump pit below deck

The existing wave flume was equipped with a motor-driven wave-generator that has a paddle that is pivoted above the crest of the flume. However, this setup produced a velocity distribution in the water column that is maximum nearer the bed and minimum at the free surface, which is not the ideal representation for modeling surface gravity waves that has minimum velocity near the bed and maximum velocity near the free surface. Therefore, the proposed solution was a paddle-type wavemaker mounted on a hinge at the flume bed. Figure 2 shows the existing wave generator setup consisting of the motor, connecting rod and paddle.

Figure 2 The existing wave generator setup consisting of the motor, connecting rod and paddle

2.2 Linear Wave and Planar Wavemaker Theories

Water waves propagating naturally towards the coast are incompressible and irrotational making its motion governed by the Laplace equation shown in Equation 1. Assuming that the wave is monochromatic, and the wave amplitude is small compared to the water depth and wavelength, the higher- order free surface boundary conditions can be linearized by applying them to the still water line instead of the water surface [19]. Applying a fixed bottom boundary condition and a periodic lateral boundary condition, the method of separation of variables will yield the solution to the Laplace equation and the dispersion relation shown in Equations 2 and 3, respectively. The dispersion relation describes the separation of waves due to different celerity of each frequency component.

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \qquad (1)$$

$$\phi(x,z,t) = -\frac{H}{2}\frac{g}{\sigma}\frac{\cosh k(h+z)}{\cosh kh}\sin(kx-\sigma t) \qquad (2)$$

$$\sigma^2 = gk\tanh kh \qquad (3)$$

where x is the direction along the propagation of the wave, z is directed upwards, $\phi(x,z,t)$ is the velocity potential at a point(x,z) at the instant, t, $H$is the wave height, g is the acceleration due to gravity, k is the wave number, h is the fluid depth, and σ is the angular frequency.

On the other hand, water waves propagating on a wave tank behave differently than on sea because of the different mode of generation and non-periodic lateral boundaries caused by a moving wavemaker. The boundary value problem from linear wave theory remains valid except for the lateral boundary condition which is now based on the horizontal displacement of the paddle producing the waves. Equations 4 and 5 show the wave height to stroke ratio generated by a flap-type paddle and piston-type paddle, respectively [20]. Both are represented graphically in Figure 3.

$$\frac{H}{S} = 4\left(\frac{\sinh kh}{kh}\right)\frac{kh\sinh(kh) - \cosh(kh) + 1}{\sinh(2kh) + 2kh} \qquad (4)$$

$$\frac{H}{S} = \frac{2\cosh(2kh) - 2}{\sinh(2kh) + 2kh} \qquad (5)$$

where S is the stroke of the paddle at still water level.

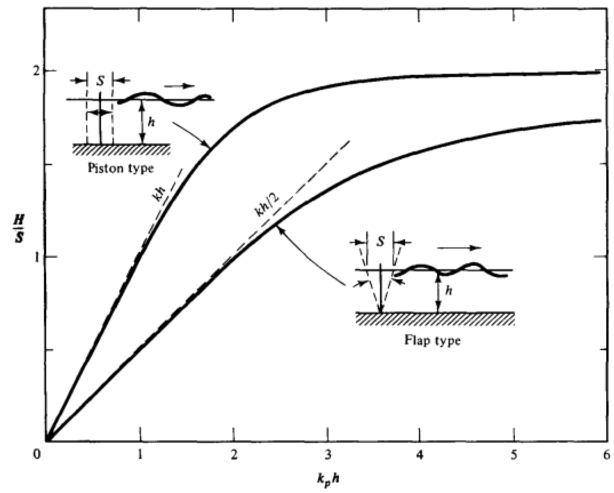


Figure 3 Wave height to stroke ratios versus relative depths for piston and flap type wavemakers [20]

It is important to note that both theories are most accurate for small-amplitude waves in intermediate to deep water. Their accuracy decreases in shallow water or for large-amplitude waves due to non-linear effects. Nevertheless, they provide simple, analytical solutions which are useful for wave generation in laboratory settings [20].

2.3 Wavemaker Selection

Wave generation in the flume can be achieved through mechanical means by a wavemaker installed at the starting point of the flume. Most wavemakers utilize oscillating members to initiate waves, creating a deformation of a vertical plane in water that corresponds to the wave's respective envelope of particle motion. The wavemaker must achieve this required deformation as close as possible in order to create stable iterations of the desired waves [21].

2.3.1 Wavemaker Types

There are a variety of options for the wavemaker. The most commonly used general category is the movable-wall type, which includes wavemakers with members that are immersed in water and oscillate back and forth. Another common general category is the plunger type, which relies on a wedge or parabolic plunger mechanism that is periodically thrust and withdrawn from the water, forming waves by water displacement. Opposed to the horizontal motion of the movable-wall type, the mechanical movement utilized by the plunger is vertical.

For the purpose of the of the ICE wave flume, the movable-wall type was considered, similar to the existing wavemaker. The existing wavemaker utilizes a rigid flap with single articulation at a hinge above the free surface, with adequate motion to produce shallow-water waves. However, articulation above the free surface produces a decrease in size of water particle orbits with depth and water leakage under the paddle results in low wave heights and may result in wave instabilities. Under the movable-wall type, the options were then shortlisted between a flap-type or a piston-type wavemaker. The flap type is composed of a rigid flap with single articulation at a hinge located at the channel bed. This type produces water motion that is suited for the generation of intermediate and deep-water waves. On the other hand, the piston type is composed of a rigid vertical wall that is moved back and forth in the longitudinal direction, suited for generating shallow-water waves. With the retrofitted flume being planned to be primarily used for physical modelling of deep water and intermediate waves, the flap type was deemed more appropriate and shall be used.

2.3.2 Wavemaker mechanisms

The motion of the hinged flap can be achieved through various mechanical configurations, fundamentally one where forward and backward motion is provided at the flap-end opposite from the hinge. Based on information initially provided by available suppliers and desk research findings, this motion can be actuated by a cam wheel connected to a variable geared motor or a pneumatic cylinder.

One of the most commonly used mechanisms for wave generators is the use of a motor that can actuate the motion of the paddle. Typically, an electric servo motor drive is used to power the movement, while the proper geometry and paddle motion range is achieved through a specialized design of a connected series of cam wheels, arms, and gears. Since the motion source is rotary, translation to linear motion is necessary. On the other hand, the pneumatic cylinder is a mechanical device that uses compressed air energy to power a recurrent linear motion and is primarily composed of a cylinder and piston. In wavemakers, the pneumatic cylinder is typically linked to a connecting rod and a slotted hinge attachment to the paddle, allowing for the motion of the paddle. Foregoing the use of wave generating software to control the flume wavemaker due to budget constraints, the pneumatic cylinder was selected over the cam wheel connected to a variable geared motor due to space limitations and ease of use.

2.3.3 Design Considerations

The main consideration in designing a wave flume is its capacity to generate waves that will suit the research agenda of the user. In our case, we want the wavemaker to be able to generate model waves similar to storm waves that have typical height of 4 to 6 meters and period of 10 to 15 seconds based on initial hindcasts in the site that we want to study. As the main restoring force in the propagation of water waves is gravity, Froude similitude has been used to determine the equivalent model wave parameters. Viscous effects were neglected by ensuring that the wave Reynolds number, given by Equations 6a to 6c, is greater than 10,000, the boundary between laminar and turbulent, oscillatory flow in the bed [22]. Similarly, surface tension has negligible effects by keeping the dimensionless parameter, Σ, given by Equation 7, less than 1 [23]. The parameter, Σ, indicates the contribution of surface tension as restoring force in the calculation of the phase speed of waves.

$$Re_b = \frac{u_b \zeta_b}{\nu} \tag{6a}$$

$$u_b = \frac{H\sigma}{2\sinh kh} \tag{6b}$$

$$\zeta_b = \frac{H}{2\sinh kh} \tag{6c}$$

$$\Sigma = \frac{\Gamma k^2}{\rho g} \tag{7}$$

where Re_b is the wave Reynolds number, u_b is the maximum near-bed horizontal velocity, ζ_b is the maximum horizontal excursion of the water particle near the bed, and, Γ is the surface tension of water.

The geometric ratio, L_r, between the model and prototype was fixed to 1:40 due to space limitations brought about by the cross-section of the original wave flume. The depth was kept at 25 cm to provide sufficient freeboard such that water will not spill as design model waves propagate. The design freeboard used was at least 2 cm plus the model wave height, corresponding to a maximum shoaling coefficient of 2. Furthermore, the length of the paddle was fixed at 50 cm since this is the vertical distance of the wave generator from the flume bed where the paddle hinge is attached. Finally, the stroke of the paddle at still water level was limited to 50 cm or 25 cm on both sides from the hinge. This corresponds to a -45° to +45° rotational motion of the paddle from the vertical as shown in Figure 4. Moving beyond this value will require a longer paddle to prevent it to be fully submerged. Subsequently, the length of the cylinder must also increase which will compromise its stability by having a longer unsupported length during wave generation.

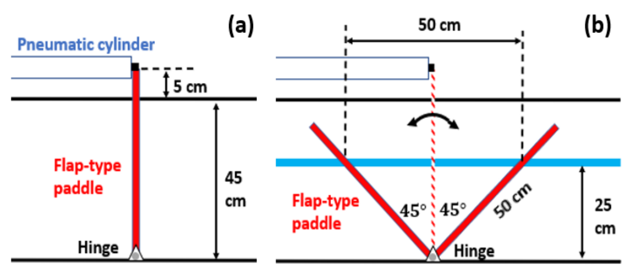


Figure 4 Vertical (a) and extended (b) positions of the wave paddle. Figure not drawn to scale.

3.0 RESULTS AND DISCUSSION

3.1 Design Parameters

The prototype depth, wave height and wave period are related to their corresponding model parameters through Froude similarity, that is, the Froude number in the model must be equal to the prototype. This is required in order to achieve dynamic similarity between inertial and gravitational forces which dominate the physical processes in wave propagation. Froude similarity yields the following relationships between the model and prototype parameters.

$$h_m = \frac{h_p}{L_r} \tag{8a}$$

$$H_m = \frac{H_p}{L_r} \tag{8b}$$

$$T_m = \frac{T_p}{\sqrt{L_r}} \tag{8c}$$

where h_m is the model depth, H_m is the model wave height, T_m is the model wave period, h_p is the prototype depth, H_p is the prototype wave height, T_p is the prototype wave period, and L_r is the geometric ratio. Note that in the succeeding calculations the subscript, m, indicating model parameters will be dropped.

The model wave height to be generated in the wave flume is directly affected by the stroke of the paddle while the model wave period is equal to the time it will take for the paddle to complete one cycle (i.e., forward-backward motion). The stroke at the still water level, S, was calculated using Equation 4, where the wave number, k, was determined from the dispersion relation in Equation 3 and the angular frequency, σ, was directly obtained from the wave period shown in Equation 9a. The wavelength, L, of the generated wave is related to the wave number, k, by Equation 9b.

$$\sigma = \frac{2\pi}{T} \tag{9a}$$

$$k = \frac{2\pi}{L} \tag{9b}$$

Other parameters considered in the design are the freeboard, f, given by Equation 10, and the required length of the paddle, L_{paddle}, that was calculated using Equation 11. An illustration of these two parameters is shown in Figure 5. In addition, the relative depth, h/L, was calculated to classify the generated wave as either, deep ($h/L \le 0.5$), shallow ($h/L \le 0.05$), or intermediate ($0.05 \le h/L \le 0.5$). The time, t_{op}, it will take for the first generated wave to return to the generator was also calculated to determine the duration at which we can perform real-time measurements before the generated waves will be contaminated by the reflected waves. Assuming perfect reflection, t_{op}, can be solved using Equation 12 and must have a value of at least 20 seconds, which we deemed as sufficient time to start, observe, and measure the generated waves during the experiments. Finally, the power needed to generate a single wave in the flume was determined and is shown in Equation 13. This parameter serves as a guide to the supplier to identify the force and pressure requirement that will drive the pneumatic cylinder during operation.

$$f = H_f - H - h \tag{10}$$

$$L_{paddle} = \frac{h + H/2}{\cos\left[tan^{-1}\left(\frac{S/2}{h}\right)\right]} \tag{11}$$

$$t_{op} = \frac{2L_f}{L/T} \tag{12}$$

$$P = \left(\frac{\rho g H^2}{8}\right)\left(\frac{1}{2} + \frac{kh}{\sinh 2kh}\right)\left(\frac{L_f}{T}\right) W_f \tag{13}$$

where f is the freeboard, H_f is the height of the flume, L_{paddle} is the required length of the paddle, t_{op} is the operation time, L_f is the clear length of the flume, P is the power required to generate one wave, and W_f is the width of the flume.

All the parameters discussed are summarized in Tables 1, 2, and 3.

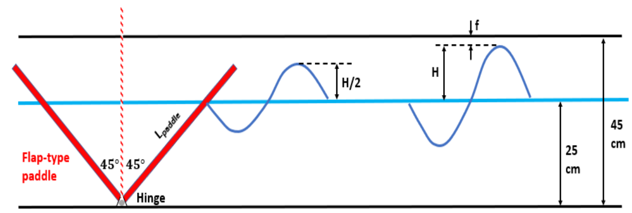


Figure 5 Illustration of the freeboard and length of the paddle. Figure not drawn to scale.

Table 1 General parameters considered in the design

Parameter	Notation	Dimension	Type	Remark
Flume height	H_f	L	Fixed	Constant at 45 cm (measured)
Flume width	W_f	L	Fixed	Constant at 60 cm (measured)
Flume length	L_f	L	Fixed	19 m excluding the space occupied by the physical model and wave generator
Density of water	ρ	ML^{-3}	Fixed	Assumed constant at 997 kg/m^3, the average value at 25°C
Surface tension of water	Γ	ML^2T^{-2}	Fixed	Assumed constant at 0.072 N/m, the average value at 25°C
Kinematic viscosity of water	ν	L^2T^{-1}	Fixed	Assumed constant at 0.0000008927 m^2/s, the average value at 25°C
Geometric ratio	L_r	-	Fixed	1:40

Table 2 Prototype parameters considered in the design

Parameter	Notation	Dimension	Type	Remark
Water Depth	h_p	L	Fixed	10 m
Wave period	T_p	T	Free	Hindcasted value of 13-15 s
Wave height	H_p	L	Free	Hindcasted value of 4-6 m

Table 3 Model parameters considered in the design

Parameter	Notation	Dimension	Type	Remark
Depth	h_m	L	Fixed	25 cm
Wave period	T_m	T	Free	
Wave height	H_m	L	Free	
Angular frequency	σ	T^{-1}	Free	
Wave number	k	L^{-1}	Free	
Wavelength	L	L	Free	
Relative depth	h/L	-	Check	> 0.05 (shallow water boundary)
Wave height to stroke ratio	H/S	-	Free	
Stroke at still water level	S	L	Free	≤ 50 cm
Freeboard	f	L	Free	≥ 2 cm
Required length of the paddle	L_{paddle}	L	Check	≤ 50 cm
Sigma parameter	Σ	-	Check	<< 1
Maximum bed horizontal velocity	u_b	LT^{-1}	Free	
Maximum horizontal excursion at bed	ζ_b	L	Free	
Wave Reynolds number	Re_b	-	Check	> 10,000
Time for first wave to be reflected and propagate back to the wave generator	t_{op}	T	Check	
Power needed to generate design waves	P	ML^2T^{-3}	Check	

3.2 Calculation Scenarios

The ideal scenario is for the wave generator to produce similar prototype waves with maximum height of 6 m and period of 15 s. However, the design should abide with all the considerations discussed in Section 2.3.3 In doing so, each parameter was classified as either: fixed, free, or check. Fixed parameters are those that cannot and were not varied in all the experiments such as the depth of the flume, the geometric ratio of 1:40, among others. On the other hand, free parameters are those that have different values on every set of calculations. Free parameters can be fixed depending on the parameter being optimized in the design. Finally, check parameters are calculated to ensure that operational considerations are achieved.

There are 12 free parameters, as listed in Tables 2 and 3, that are dependent on each other through Equations 3, 4, 6b, 6c, 8b, 8c, 9a, 9b, and 10. In order to acquire a unique solution on each set of calculations, 2 of these 12 free parameters were assigned its maximum value in the design process. All set of calculations made were summarized in Table 4. In the initial calculations, denoted as C_0, the prototype wave height of 6 m and prototype wave period of 15 s were set as fixed parameters. This is to determine the required stroke necessary to generate similar porotype waves with aforementioned maximum properties. Results suggest that the limited stroke at still water level of 50 cm is not sufficient to generate the desired maximum waves. In addition, this case will require a longer paddle and angle of rotation from the vertical of more than 45°. This means that the ideal situation cannot be achieved with the given operational restrictions of the wave flume. As such, a new set of design calculations was performed to determine the maximum properties of the waves that the generator can produce given the restrictions. In this calculation, denoted by C_1, the stroke at still water level was maximized at 50 cm and the allowable freeboard was minimized at 2 cm. Similar prototype waves of 7.2 m height and 9.80 s period were calculated indicating unacceptable values for both parameters, with height exceeding the 6 m hindcasted maximum value and period below the hindcasted minimum of 13 s. Two more sets of calculations, denoted by C_2 and C_3, were done where the stroke of the cylinder was fixed at 50 cm. In C_2, the other fixed parameter is the prototype wave height at 6 m while in C_3, the prototype wave period was fixed at a value of 15 s. The purpose of these two sets of calculations is to determine the prototype parameter corresponding to the maximum, similar, prototype wave height (C_2) and wave period (C_3) that can be generated in the wave flume. The two sets of calculations yielded acceptable values within the hindcasted range of prototype wave parameters. This indicates that although prototype waves with simultaneous maximum properties cannot be generated in the wave flume, it can produce 6-m high similar prototype waves with period of 11.4 s or 15-s period similar prototype waves with height of 4.4 m.

Further analysis of Equations 3, 4, and 9a shows an inverse relationship between the model wave height, H, and period, T, that can be generated by the paddle. As seen in Figure 1, the value of H/S increases as the value of kh increases. If h and S are constants, it follows that k and H will have a direct relationship despite having the variable, k, in the denominator. Similarly, the dispersion relation in Equation 3, implies that σ also increases with k at a constant value of h. Through the principle of transitivity, if H increases as k increases, and k increases as σ increases, it follows that H increases as σ increases. Furthermore, we know from Equation 9a that T is inversely proportional to σ. Hence, we can conclude that as H increases, T decreases, and vice versa, indicating the inverse relationship between the height and period of the waves that can be generated by the paddle. In C_1, the model wave height was maximized by minimizing the freeboard to 2 cm, limiting the model wave period to a minimum. This relationship was also illustrated in cases C_2 and C_3. Based on this observation, another set of calculations, denoted by C_4, was performed where we determined the simultaneous, similar, prototype wave conditions. This calculation is similar to C_0 but instead of using maximum values of 6 m for prototype wave height and 15 s for prototype wave period, we determine, through an iterative process, the combination that will yield the simultaneous maximum for the 2 parameters. This calculation yielded a value of 13.1 m and 5.1 s for the similar prototype wave height and period, respectively.

Table 4 Summary of all parameter values for each calculation scenario

Parameter	Unit	C_0	C_1	C_2	C_3	C_4
H_f	cm	45				
W_f	cm	60				
L_f	m	19				
ρ	kg/m³	997				
Γ	N/m	0.072				
ν	m²/s	0.0000008927				
L_r	-	**1:40**				
h_p	m	**10**				
T_p	s	15*	9.80**	11.43 **	15*	13.1*
H_p	m	6*	7.2**	6*	4.42**	5.1*
h_m	m	**0.25**				
T_m	s	2.372	1.549	1.807	2.372	2.071
H_m	m	0.15	0.18	0.15	0.111	0.128
σ	rad/s	2.649	4.057	3.477	2.649	3.033
k	wave /m	1.744	2.786	2.341	1.744	2.016
L	m	3.603	2.255	2.684	3.603	3.117
h/L	-	0.069	0.111	0.093	0.069	0.080
H/S	-	0.221	0.360	0.300	0.221	0.257
S	m	0.678 **	0.5*	0.5*	0.5*	0.496 **
f	m	0.05	0.02*	0.05	0.089	0.073
L_{paddle}	m	0.548 **	0.481 **	0.460 **	0.432 **	0.442 **
Σ	-	0.0000223**	0.0000572**	0.0000404**	0.0000224**	0.0000299**
u_b	m/s	0.442	0.484	0.421	0.326	0.368
ζ_b	m	0.167	0.119	0.121	0.123	0.121
Re_b	-	82477 **	64702 **	57130 **	44835 **	49985 **
t_{op}	s	27.5	26.1	25.6	25.0	25.3
P	W	23.6	30.1	22.1	12.8	16.6

*optimized parameter (fixed)
**check parameter (red font indicates non-compliance with design specifications)

3.3 Final Design of Wave Generator

The final design of the wave generator is a flap-type, 50-cm long, paddle that is hinged at the bottom and connected on the top end to a pneumatic cylinder. It can rotate about the hinge up to ±45° from the vertical with a maximum stroke of 50 cm at still water level. The paddle is wet on both sides, so it is placed 1.5 m from the flume entrance to provide sufficient space for a passive wave absorber on the opposite direction of wave propagation. Another wave absorber will be placed at the end of the flume. The purpose of these wave absorbers is to reduce wave reflection to a negligible value so it will not affect the properties of propagating waves through wave reflection. Each wave absorber will have a slope of 1V:2H (~27°) made of gravel with wire screen frame on the sloping surface. The low slope angle and the use of hard fill material are sufficient to reduce the reflection coefficient of the absorber to at most 10% [24]. The design depth in the flume is 25 cm and the recommended geometric scale is 1:40. At a maximum stroke of 50 cm at still water level, it can generate similar, prototype waves with height of 5.1 m and period of 13.1 s. Higher than the design wave height or period can be generated at the expense of the other parameter as shown in the results of calculations C_2 and C_3.

Smaller and shorter period waves can be generated by controlling 2 parameters: stroke of the cylinder and the pressure inside the pneumatic cylinder. The stroke of the cylinder is the distance that the cylinder will travel. We can control the starting point and end point of this stroke using sensors which is related to the stroke at water level of the paddle via geometry. The pressure inside is the force that drives the forward-backward motion of the cylinder. Adjusting the pressure varies the time it takes for the cylinder to cover 1 cycle which is equal to the period of the wave it will generate.

3.4 Wave Flume Extension

The existing wave flume is 9-meter long and is proposed to be extended to facilitate a longer time window that is convenient for the end-users. Since the proposed new wavemaker to be installed is not absorbing type, it is expected that reflected waves from the model section of the flume will disturb the incoming waves from the wavemaker section yielding incorrect measured wave properties. The proposed solution is stopping wave generation once reflected waves reach the wavemaker section. As such, the wave flume must be long enough so that there is sufficient time window of recorded wave data to determine pertinent wave properties such as height and period.

The wave flume is to be extended from 9 meters to 22 meters, which is the maximum allowable length due to to space constraints of the laboratory. At extreme model wave conditions, it is estimated that we will have about 25 seconds to conduct measurements, from generation of initial wave until the time it is required to stop due to reflected waves.

4.0 CONCLUSION

This study highlights the concept design of the wave flume to be retrofitted in the Institute of Civil Engineering Coastal Engineering Laboratory. A flap-type paddle that is hinged at the flume bed was selected as the wavemaker that theoretically, can produce waves up to 12.8 centimeters high and period of 2.1 seconds, equivalent to prototype waves with height of 5.1 meters and period of 13.1 seconds at a fixed geometric ratio of 1:40. The flume will be extended to 22 meters in order to provide sufficient time window for measurements before the reflected design waves pollute the waves generated by the wavemaker. A schematic of the setup of the instruments in the wave flume is shown in Figure 6.

While procuring a brand-new wave flume is the ideal scenario, retrofitting an existing flume is more advantageous as it is cost effective and can be implemented sooner in relation to our project. In addition, this research will pave the way to the use of physical models in coastal engineering research in our country. Finally, our research can be used by other universities in designing their own low-cost wave flumes that can be used for instructional purposes.

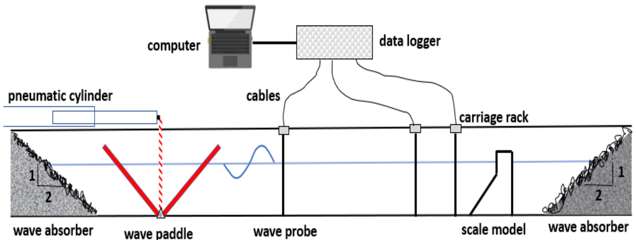


Figure 6 Schematic of the instruments to be used in wave flume experiments.

Acknowledgement

The authors would like to thank the Department of Public Works and Highways (DPWH) for providing the funding used through the project "Feasibility Study and Detailed Engineering Design for the Proposed Seawall Alignment in the Municipalities of Minalabac, Pasacao and San Fernando, Camarines Sur", the University of the Philippines National Engineering Center (NEC) for providing administrative support, and the technicians and consultants who have shared their expertise in the development of the concept design.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

References

[1] Department of Environment and Natural Resources (DENR), Bureau of Fisheries and Aquatic Resources (BFAR) of the Department of Agriculture (DA) and Department of Interior and Local Government (DILG). 2001. *Philippine Coastal Management Guidebook No. 1: Coastal Management Orientation and Overview*. Coastal Resource Management Project of the Department of Environment and Natural Resources, Cebu City, Philippines, 58.

[2] Cunanan, T.A.R.A., Legasca, E.F.L., Noriega, C.J.J. and Cabauatan, R. 2022. Damages Caused by Natural Disasters and the Number of Natural Calamities' Effect on Philippine Government's Spending on Disaster Management. *Malaysian Journal of Social Sciences and Humanities.* 7(2): e001284. DOI: https://doi.org/10.47405/mjssh.v7i2.1284

[3] Abundo, M., Nerves, A., Paringit, E. and Villanoy, C. 2012. A Combined Multi-Site and Multi-Device Decision Support System for Tidal In-Stream Energy. *Energy Procedia.* 14: 812-817. DOI: https://doi.org/10.1016/j.egypro.2011.12.1016

[4] Bautista, D.M., Herrera, E.C. and Cruz, E.C. 2024. Assessment of Morphological Dynamics in Ibajay, Aklan Coast using Delft3D Numerical Simulation. *Philippine Engineering Journal.* 45(1): 57-76.

[5] Santos, F.D., Herrera, E.C., Hernandez, B.C.B., Dela Cruz, G.E.T., Almarza, F.H.D.M., Basina, R.M., Yoshikai, M. and Nadaoka, K. 2024. Modelling the Sediment Dynamics of a Developing Coastal Estuary: The Case of Batan Bay, Aklan. *Philippine Engineering Journal*. 45(1): 29-56.

[6] Villalba, I.B.O., Cruz, E.C. and Adame, A.A.A. 2022. Assessing the Effects of Different Typhoon Tracks on Storm Surge Generation in Manila Bay using ADCIRC. *Philippine Engineering Journal.* 43(1): 22-46.

[7] Amedo-Repollo, C.L., Flores-Vidal, X., Chavanne, C., Villanoy, C.L. and Flament, P. 2021. Barotropic and Baroclinic Tides in Panay Strait, Philippines. *Regional Studies in Marine Science.* 41: 101612. DOI: https://doi.org/10.1016/j.rsma.2021.101612

[8] Ringor, C.L. and Siringan, F.P. 1998. Net sediment transport in Pampanga Bay, northwestern Manila Bay, derived from grain size trends, bathymetric change and landsat data. *The Philippine Agricultural Scientist*. 99(1):68-79.

[9] Siringan, F.P., Berdin, R. and Sta. Maria Y. 2004. *Coastal erosion in San Fernando, La Union: Trends, causes and possible mitigation measures* [terminal report]. Marine Geology Laboratory, National Institute of Geological Sciences. University of the Philippines Diliman. 61.

[10] Soria, J.L.A., Switzer, A.D., Pilarczyk, J.E., Siringan, F.P., Khan, N.S. and Fritz, H.M. 2017. Typhoon Haiyan Overwash Sediments from Leyte Gulf Coastlines Show Local Spatial Variations with Hybrid Storm and Tsunami. *Sedimentary Geology.* 358: 121-138. DOI: https://doi.org/10.1016/j.sedgeo.2017.06.006

[11] Hughes, S.A. 1993. *Physical Models and Laboratory Techniques in Coastal Engineering.* 7. World Scientific.

[12] Hughes, S.A. 2014. Coastal Engineering Challenges in a Changing world. *Journal of Applied Water Engineering and Research.* 2(2): 72-80. DOI: https://doi.org/10.1080/23249676.2014.977360

[13] Couriel, E., Nielsen, L., Jayewardene, I. and McPherson, B. 2018. The Need for Physical Models in Coastal Engineering. *Coastal Engineering Proceedings.* 36: 52. DOI: 10.9753/icce.v36.structures.52

[14] Ismail, H., Abd Wahab, A.K. and Alias, N.E. 2012. Determination of Mangrove Forest Performance in Reducing Tsunami Run-up Using Physical Models. *Natural hazards.* 63: 939-963. DOI: https://doi.org/10.1007/s11069-012-0200-y

[15] Nguyen, N.M., Van, D.D., Le, D.T., Cong, S.D., Chuong, L.T., Hai, T.D., Nguyen, T.C., Wright, D., Tanim, A.H., Pham, N.T., Thanh, P.N. and Anh, D.T. 2023. Experimental and Numerical Modeling of Pile-Rock Breakwater Gap Arrangement for Optimal Coastal Erosion Protection in Deltaic Coasts. *Ocean Engineering*. 280: 114625. DOI: https://doi.org/10.1016/j.oceaneng.2023.114625

[16] Arifullah, A., Pratama, N., Zein, I., Nazaruddin, Usman, T., Ibrahim, I. and Benazir, B. 2023. Imaging of Hydrodynamic Field Around Submerged Objects Regular Wave and Tsunami Conditions. *E3S Web of Conferences.* 447: 01011. DOI: 10.1051/e3sconf/202344701011

[17] Asian Institute of Technology Water Engineering and Management. Facilities. ait.ac.th. Accessed June 24, 2024. [Online]. Available: https://wem.ait.ac.th/facilities/.

[18] Tapaoan, D.P.J. MMSU launches coastal eng'g R&D center. mmsu.edu.ph. Accessed June 24, 2024. [Online]. Available: https://www.mmsu.edu.ph/news/mmsu-launches-coastal-engg-rd-center.

[19] Airy, G.B. 1845. *Tides and Waves*. Encyclopedia Metropolitana.

[20] Dean, R. and Dalrymple, R. 1991. *Water Wave Mechanics for Engineers and Scientists.* World Scientific.

[21] Chappell, E. R. Theory and design of a wave generator for a short flume. M.S. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, Canada. 1969. [Online]. Available: https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/831/items/1.0050588. DOI: 10.14288/1.0050588

[22] Kamphuis, J.W. 1975. Friction Factor under Oscillatory Waves. *Journal of the Waterways, Harbors and Coastal Engineering Division*. 101: 135-144.

[23] Uchiyama, Y. 2019. Surface Gravity and Capillary Waves. Encyclopedia of Ocean Sciences, 3rd Ed. 3: 672-681. DOI: https://doi.org/10.1016/B978-0-12-409548-9.11465-4

[24] Lim, H.C. 2014. Optimum design of a sloping-wall-type wave absorber placed in a sinusoidal propagating wave. *Ocean Engineering*. 88: 588-597. DOI: https://doi.org/10.1016/j.oceaneng.2014.03.029.