Proceedings of ASME 2023
International Mechanical Engineering Congress and Exposition
IMECE 2023
November 1 – 5, 2023, New Orleans, LA, USA

IMECE2023-110631

CURVED SEAWALLS AS AN EROSION MANAGEMENT TOOL FOR SAIPAN

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ABSTRACT

The purpose of this research is to address the problem of coastal erosion on Saipan's main highway, Beach Road, by analyzing what type of curved seawall would be most effective at reflecting wave energy. This project is motivated by is the challenge of coastal erosion, which has already become a major problem for many Pacific Islands. If left unaddressed, coastal erosion and inundation will leave many islands in economic and societal ruin, as these islands build their communities and infrastructure along their coastlines. As communities on these islands have a vested interest in preserving their seaside infrastructure, our goal is to provide these islands with information related to seawall type, overtopping potential, and potential failure points of the seawall face.

OpenFOAM is an open-source computational fluid dynamics (CFD) solver that solves the coupled Navier-Stokes Equations using finite volume methods. Our experimental work began with the adaptation of a baseline dam break simulation in OpenFOAM to simulate a single crashing wave. The seawalls were then traced, and their geometries were developed into a triangular mesh using Salome. Once developed, our geometries were then taken to OpenFOAM where the files with the initial conditions, parameters, and system dictionaries were kept constant and new geometries were tested with the shape of the water column.

We then compared the fluid behavior in OpenFOAM with a physical experiment using 3-D printed scaled models and a digital hydraulic bench. Through OpenFOAM simulations we confirm that curved seawalls performed well for reducing overtopping and reflecting waves when compared to a VW and inclined wall. Of the three curved seawalls, a parabolic seawall performed best at reflecting waves. We also observe significant pressure near the recurve area of the model-CPS seawall from the wave crashing onto it. We were able to confirm that wave behavior in OpenFOAM was accurate through our physical experiments where we observe wave reflection and wave overtopping.

Optimizing seawall geometry is crucial for islands that rely on coral reefs for managing waves as reefs are predicted to die en masse as climate change continues, thus leaving islands more exposed than ever. While this study was able to confirm wave reflection amongst the proposed seawalls, further modeling of coastline sediment, lagoon structure and ecosystem, and weather effects on sea level is required to create a more holistic coastal defense solution that remains effective for the rapidly changing future.

NOMENCLATURE

CFD	Computational Fluid Dynamics
CPS	Curved seawall consisting of a quarter circle joined with a parabola. [14]
DGH	Digital Hydraulic Bench
FSS	Curved seawall formed by varying nine radii that increase in length from bottom to top. [14]
GIS	Geographic Information System

FIGURE 1: Overview of Saipan (left), with flood hazard zones and flood masks highlighted in yellow and blue. The right figure is zoomed in at the section of Beach Road that this project focuses on. It is also where Beach Road is closest to the Saipan lagoon [4].

GS	Curved seawall formed by combining curvature of two circles with different radii. [14]
g	Gravitational constant $[ms^{-2}]$
IW	Inclined Wall
σ	Phase Properties
ν	Kinematic viscosity $[m^2s^-1]$
ρ	Density of fluid $[m^3]$
p	Pressure [Pa]
t	Time [s]
u	Velocity vector $[ms^{-1}]$
USACE	United States Army Corps of Engineers
UTE	Uniform triangular elements
VW	Vertical wall

1 Introduction

The effects of climate change and rising sea levels can be readily observed in the United States' territories in the Pacific [9]. These Pacific islands have little to no effect on climate change yet bear a greater burden than the countries that are responsible for climate change [9]. Saipan is one such island (Figure 1); it is experiencing a declining coastline, crumbling pathways, and once-in-a-century typhoons more frequently [6]. The negative effects of climate change on Saipan are innumerable; thus, we have taken on the task of exploring how an increased frequency of storms, wave-energy return, and median sea level rise affects a major thoroughfare in Saipan, Commonwealth of the Northern Mariana Islands (CNMI).

Beach Road is an arterial thoroughfare that services the island's most populous westward side [12]. The westward side of Saipan is where a majority of businesses are located and is only a stone's throw away from the water at its closest point [12]. The coastline that it spans is roughly five to ten feet above sea level at the high water mark [6]. This places the entirety of Beach Road at risk of coastal inundation [4]. Coastal inundation occurs when the sea level rises to the point where buildings and infrastructure become flooded. Portions of Beach Road are left uniquely vulnerable to coastal inundation as wave run-up, the highest point that a wave travels onshore, causing the road's foundation to erode as shown in Figure 2. Although waves often reach the base of Beach Road during storm surges, this project is concerned with the section located at the intersection of Beach Road and Monsignor Guerrero Road (see Figure 1) as it serves as a major junction point for the island's traffic [6].

This section of Beach Road is most concerning because of a pathway/walkway that runs alongside the southbound side of the highway. Additionally, this section is the closest part of the highway to the lagoon. Currently, the walkway's concrete structure and the rapid change in gradient serve as a sort of crumbling seawall. However, this elevated walkway is experiencing major deterioration due to wave run-up and rust, and will eventually collapse. The collapsed pathway will then act as a ramp for waves, making Beach Road more vulnerable to flooding. The rapid change in gradient coupled with significant amount of beach erosion will translate into waves crashing closer to the base of Beach Road and the walkway. Erosion at this section of Beach Road is a major problem as it can quickly eat away at the structure supporting the road itself as seen in Figure 2. Further, one can observe the failing structure and eroding coastline in Figure 2. Notice that the trees that line Beach Road now have exposed roots and

FIGURE 2: (Left) Beach Road, prior to Typhoon Yutu in 2015 and (Right) Beach Road Today, October, 2022. The effects of Typhoon Yutu, Typhoon Soudelor, and many more tropical depressions have caused the face of Beach Road to drastically change. The first change is a decrease in the number of trees that act as a natural support structure of the coastline. The second is a significant change in the berm due to sediment loss. (Left Picture Credit: U.S. Army Corps of Engineers)

FIGURE 3: Beach Road and the pathway that runs parallel to it. In the right picture we can readily observe how waves have eroded away sediment such that tree roots have become exposed. Further, notice that waves have caused a vertical drop to develop. The exposed tree roots indicate that this "buffer zone" was covered with soil, but a constant barrage of waves and storms has altered Saipan's coastline. It is important to note that waves do not normally reach this buffer zone under normal tidal fluctuations. Instead, this erosion is indicates that waves now have enough energy to traverse Saipan's barrier reef and reach the buffer zone of Beach Road.

their collapse would further exacerbate the problem of an unstable foundation. The effects of an unserviceable Beach Road would be crippling for the island. They would result in a standstill for most of the island's activities and population. The goal of this project is to motivate local officials to start implementing a solution by constructing a seawall. This paper focuses on what type of seawall would be most effective at reflecting waves away from Beach Road. To address this question, we have developed a computational fluid dynamics model and run experimental scaled tests for different seawall geometries.

2 Background

As a tropical island, tourism is Saipan's main export. It is located within a four-hour flight from major cities like Seoul, Busan, Tokyo, and Beijing, making it a prime location for a weekend getaway for those wanting to visit a U.S. territory. Despite this, the U.S. Army Corps of Engineers (USACE) had to termi-

FIGURE 4: The upper picture showcases the power of waves as one can observe exposed concrete reinforcing bars. In the lower picture we can observe collapsed or missing sections of an accessibility ramp from the walkway to the beach. These observations were the basis for testing our inclined wall seawall as there is potential for the water facing beams to collapse. This would then act as an inclined ramp for waves to travel over and onto Beach Road. Pictures taken in summer 2022.

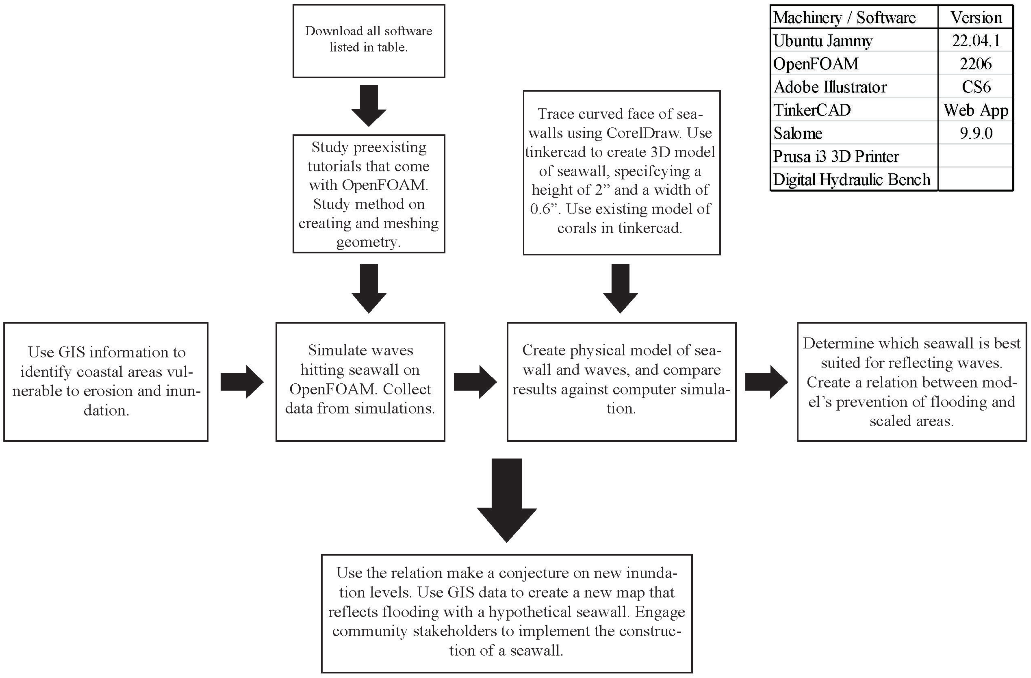
nate a feasibility study on the fortification of Beach Road against the problems that come with climate change at the request of the C.N.M.I. government [13]. The primary reason for this termination was the insistence by the C.N.M.I. government to implement “nature-based solutions” [13]. The desire for a more natural form of coastal defense stems from tourism in that they may not want to visit an island with concrete seawalls spoiling the pristine atmosphere of a beach getaway. Some examples of nature-based solutions involve the cultivation of mangroves or other plants that do well in high salinity environments while at the same time reducing wave energy from impacting the span of Beach Road. However, investments into nature-based solutions are not optimal as such solutions are not expected to survive in high energy wave environments, such as Saipan’s lagoon [13]. Further evidence pointing away from nature-based solutions comes in the form of an investment loss as these nature-based solutions, *vegetation only alternatives*, over a fifty-year evaluation period, are expected to cost \$23,000,000 and yield a net loss of \$1,014,500 [13].

The same is not true when it comes to constructing a hybrid seawall, according to the U.S. Army Corps of Engineers [13]. While the USACE’s version of a seawall may not be the same as the one that this paper is studying, it is expected that a seawall directly in front of or immediately seaward of the Beach Road walkway, along with the plantation of vegetation to increase sediment stability, and the placement of edging or sills to reduce erosion, has a total project cost of \$39,500,000 with net benefits in \$1,322,700 [13]. The decision to terminate this study, in the face of overwhelming evidence that building a seawall would be beneficial, is a problem that many low-lying communities across the United States must reckon with as there will be a point in time when building a seawall comes too little too late [5]. The motivation to continue studying what type of seawall would work best aligns with providing alternative responses to climate change given that Saipan’s barrier reef, an island’s natural form of protection against waves, could potentially die en masse as global mean temperatures rise [11].

As there were no specifications regarding the type of seawall that would be built had the C.N.M.I. government gone forward with the feasibility study, we have focused on using OpenFOAM [8], a program that is used to model fluid dynamics, to determine which type of seawall works best at reflecting waves away from the coastline using shapes selected from Sundar and Anand’s study [14]. In addition, we have constructed simulations in which an inclined wall (IW) represents a collapsed pedestrian walkway (see Figure 4) to study how waves travel up the incline. We expect that the water will either have enough energy to travel over the incline and onto Beach Road causing it to flood or it will fall through the gap that exists between the inclined seawall and berm of Beach Road, resulting in more sediment erosion and worsening the support base of Beach Road.

3 Methods

We began with a brief geospatial and physical analysis of Saipan’s westward lagoon using data from the USGS and on-site inspections to determine what section of Beach Road would most benefit from the construction of a seawall. The site where Figures 1, 2, and 4 are located was chosen because of the exposure of Beach Road’s foundation to waves, its proximity to water, gradient change, and significance as a major junction point to Middle Road, Saipan’s main highway. Geographic information system (GIS) data from the United States Geological Survey was used to determine the extent of coastal inundation and flood hazard



Machinery / Software	Version
Ubuntu Jammy	22.04.1
OpenFOAM	2206
Adobe Illustrator	CS6
TinkerCAD	Web App
Salome	9.9.0
Prusa i3 3D Printer	
Digital Hydraulic Bench	

FIGURE 5: Diagram of methods.

zones for the focus area as seen in the Figure 1 [4].

Prior to both experiments, the shapes of four different seawalls were selected from Sundar and Anand's [14] study on run-up on curved seawalls. These curves were traced with Adobe Illustrator [1]. Computer simulations started with mesh generation using the open-source tool Salome. Triangles with areas varying in size from 0.00005 to 0.001 made up the test area. Meshes were then converted for use into OpenFOAM [8] where boundary conditions, physical parameters, and system parameters were set to simulate a fluid's impact on seawalls.

Seawalls for physical experiments were generated by using the same shapes, but were extruded in TinkerCad [2] to be 5.8 cm tall, with its length being proportionally derived by maintaining the ratio between width and height when stretching the shapes. The width was made to be 1.524 cm to match the digital hydraulic bench's chamber width. Seawalls were then placed in the chamber with water. Tests were performed with water heights of 1.6 cm or 2.9 cm. Waves were generated by moving a wall(wave generator) back and forth with varying intensity to simulate different phase velocities. The diagram of methods in Figure 5 is an overview of the steps taken to form this project.

3.1 Types of Seawalls

The seawalls for this study are shown in Figure 6. The vertical wall case resembles what is currently happening with Beach Road. Years of erosion have led to a VW forming at the seaward edge of Beach Road. This VW is primarily made up of soil and will continue to erode inland unless a structure is put in place to reflect wave energy away from it. A good example of the power that waves possess is its effects on the seaward side of Beach Road prior to 2015 and to Beach Road in 2022 (Figure 2). In the approximately seven years between the photos, the gradual downward slope has been transformed into a VW by waves constantly crashing onto and eroding away at the soil. This problem is further compounded by super-typhoons which bring low pressure systems into the area that allows for a temporary rise in wind speed, sea level and higher transmission of wave energy over Saipan's barrier reef into the lagoon and subsequently the coast. These super-typhoons also result in trees collapsing, further decreasing the soil stability along the coast. This vicious cycle of consistent erosion, loss of trees as coastal fortifications, and higher wave energy transmission will inevitably lead to the failure of Beach Road.

The inclined wall (IW) case represents what could happen if the raised walkway collapsed (Figure 4). The raised walkway is showing signs of deterioration, such as exposed reinforcement bars and missing sections of the pathway, on the sides directly exposed to the waves. In the event that this pathway should collapse, it would most likely collapse at the side that experiences the most impact from waves. This could lead to a scenario in which the pathway acts as an inclined ramp for waves to accelerate onto and cross over to Beach Road.

The remaining seawalls were chosen from Sundar and Anand's research [14]. They consist of the CPS, FSS, and GS curved seawalls. These curved seawalls allow for water to be reflected away from the coastline. The differences between these seawalls is the location of the curve's inflection point, length of overhangs, and the distances that water will travel prior to reflection. The FSS seawall was formed by varying nine different radii and the GS seawall was formed by the combination of two radii of curvature, a suggestion by the U.S. Army Corps of Engineers [14]. The CPS curve is a parabolic curve at the bottom with a quarter circle at the re-curved portion which was smoothly connected at the intersection [14].

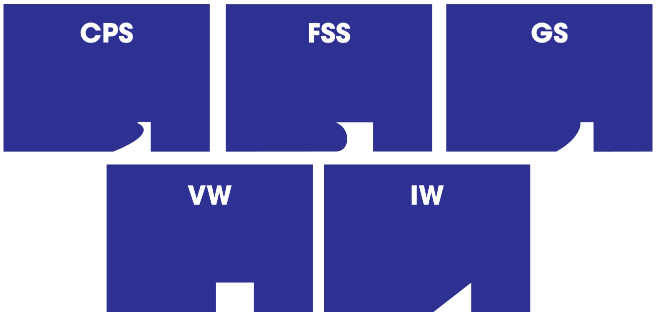


FIGURE 6: Five shapes of possible seawalls; a single wave will start as a column of water (not shown) to the left of the seawall and crash towards the right onto the seawall.

3.2 Computational Methods

Simulations on various curved seawalls were done in OpenFOAM. We considered several types of seawalls, including square (VW) and the curved seawall (CPS, FSS) as they reflects the energy of the wave effectively and is more likely to prevent the water from reaching the shore. OpenFOAM solves the coupled Navier-Stokes Equations using finite volume methods. This is appropriate for us, as our model is best described by the Navier-Stokes equation. An incompressible fluid is a fluid whose *density* does not change with *pressure* [7].

$$\rho \frac{Du_i}{Dt} = -\frac{\partial p}{\partial x_i} + \rho g_i + 2\mu \frac{\partial e_{ij}}{\partial x_j} - \frac{2\mu}{3}\frac{\partial}{\partial x_i}(\nabla \cdot \vec{u}) \tag{1}$$

where ρ is the density of the fluid, u is the velocity vector of the fluid, μ is the viscosity of the fluid, and p is the pressure. For the CFD model the flow is multiphase, so the pressure p is expressed in terms of gravity and the hydrostatic pressure. We now note that $\nabla \cdot \vec{u} = 0$, and using vector notation, we get:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{u} \tag{2}$$

For the boundary conditions, we used a no-slip ($u = 0$) condition for the velocity on the seawall and the other solid surfaces. For the initial condition, we used an initial volume of water at $t = 0$ that represented the incoming wave volume. To reduce computational time we limited the CFD model to one wave to consider the impact and effects on each seawall.

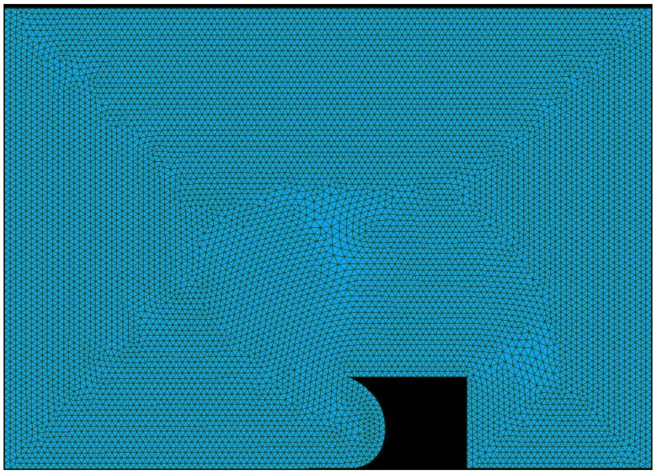


FIGURE 7: Triangular mesh for FSS seawall with 17,104 UTE.

Computer modeling for this project started with mesh generation using the open-source tool Salome [15]. Salome's `NETGEN 1D-2D` algorithm with `NETGEN 2D Parameters 1` hypothesis were used to generate uniform triangular elements (UTE) with an area of 0.5 and a fineness of *Very fine* [15]. The IW seawall consisted of 17,140 UTE, VW seawall 16,798 UTE, GS seawall 17,075 UTE, CPS seawall 17,363 UTE, and FSS seawall 17,104 UTE. These geometries were then extruded to have a height of 0.2cm. While this would imply that our triangles are in fact prisms, OpenFOAM requires geometries to be at least one cell width thick in order to conduct 2-D simulations [8]. The mesh for all five seawalls were then converted for use in OpenFOAM using the `ideasUnvToFoam` function after which boundary conditions, constants, and system parameters were set to simulate a single wave impact on the seawalls.

Prior to finalizing the above geometries for our CFD model, we performed a mesh resolution study to understand how different mesh levels would affect our simulations. We found a computational limit to our mesh resolution at about 17,000 UTE using the algorithm and hypothesis specified in the previous paragraph.

We also tested geometries with variable size triangular elements of 0.0003 to 0.006 and found that local mesh refinement in areas with greater curvature or angles created unrealistic fluid behaviors.

3.3 Experimental Methods

Seawalls for physical experiments were generated by using the same trace, but were extruded in TinkerCad to be 5.8 cm tall, with their length being proportionally derived. The width was made to be 1.524 cm to match the DGH's chamber width. Seawalls were then placed in the chamber with water. Tests were performed with water heights of 1.6 cm or 2.9 cm. Waves were generated by moving a wall(wave generator) back and forth with varying intensity to simulate different phase velocities.

We 3-D printed several types of seawalls and placed them into our DGH which is a small experimental water flume. The flume allows control of the fluid flow rate, fluid height, and allows us to put the seawall into an enclosed two dimensional channel. This experimental system allows us to approximate a 2-D wave event similar to that of our OpenFOAM simulations.

In order to generate our waves we first 3-D printed a wall that had a width of 1.47cm which was designed to be a smaller width than the DGH's chamber to allow for the back-and-forth movement of the wall. The rectangular object is made to travel a distance of about 12.5cm along the length of the wave chamber. We generated waves based on two velocities, a high velocity and low velocity movement of the rectangular object, and two water levels 1.6cm and 2.9cm. The average speed for the high velocity was measured to be about 0.12 centimeters per second or 1.2 millimeters per second.

Seawall models were uniformly constructed to be about 5.08cm tall. The curved faces of the GS, FSS, and CPS seawalls were approximated from Sundar and Anand's paper on Dynamic Pressure and run-up on curved seawalls compared with VW under cnoidal waves [14]. The faces of the curved seawalls were then scaled proportionally to reach a height of 5.08cm. All five of our seawalls were printed using Polylactic Acid (PLA) filament.

4 Results

4.1 Computational Results

The OpenFOAM modeling results are shown in Table 1, Table 2 and Figure 9. The simulations that produced the results in Table 1 used variable triangular elements. Unexpected fluid behavior was observed in the form of fluids seemingly sticking longer on the upper-left corner of seawalls. This upper-left location corresponds to a finer mesh, which creates an opportunity to enhance our CFD models. The goal we had hoped to achieve with varying triangle sizes is to have a finer triangular mesh surrounding the seawall and a coarser mesh everywhere else. This would allow us to better observe and understand fluid behavior as it hits the faces of the seawalls without having to waste computational resources on areas of the geometry that do not need to be calculated. Although a very fine mesh for the entirety of the geometry is ideal, computational and hardware limitations required us to use a coarser method.

The results from Table 2, which uses UTE, produced results most similar to our physical experiments and will be discussed below. Computer simulations used a block of water with size 1.5 cm in the x-direction $\times$ 1 cm in the y-direction to represent a singular wave. The singular wave in our simulations was reflected in all seawall types except the inclined wall. Significant wave overtopping was observed for the VW, IW, and GS seawalls. The VW and GS seawalls produced similar fluid behavior in that maximum wave height was nearly double that of the seawalls itself. The lack of a curved cover on the GS seawall allowed for waves to travel up and land on top of the seawall subsequently allowing water to land behind the seawall.

The IW seawall represents a scenario in which Beach Road pathway collapses. Out of the four other seawalls, the IW seawall allowed for the most amount of water to land behind it. The wave was able to clear the same amount of distance as the length of the IW seawall. In fact, the wave formed a path similar to that of the IW seawall but in the opposite direction. We would expect a significant amount of coastal inundation to occur if the Beach Road pathway collapses. Out of the five seawalls, the FSS and CPS seawall performed the best at reflecting the singular wave and preventing overtopping in the CFD model.

While both the FSS and CPS seawalls performed well at reflecting waves, the CPS seawall experienced significant localized pressure where the wave's momentum changes to reflect in the opposite direction. That area in which the momentum changes in the CPS seawall is called the recurve area and the maximum value of pressure experienced was 88,000Pa. The FSS seawall actually experienced greater pressure values with a maximum of 96,000Pa, but this pressure was observed to be evenly distributed along the entirety its curved face. Still, these high-pressure areas could potentially lead to structural failure of the seawalls as they experience a constant barrage of seawater. This constant barrage of seawater will eventually erode away at the concrete and reinforcement bars that the seawalls would be built out of. Figure 4 is a perfect example of how even a vertical column, which would experience less localized pressure than the CPS seawall, can fail overtime without a curved face. It is not hard to imagine that if waves can do so much damage to a vertical column of concrete, that a seawall with a high-pressure point will experience the more damage at a faster rate.

4.2 Experimental Results

The experimental results are shown in Table 3 and Figure 9 for the FSS seawall. The 3-D printed seawall is shown in red.

TABLE 1: Computer Model of Waves Hitting Seawalls with variable triangular elements. 1.5cm x 1cm Block of Water.

Type of Seawall	Wave Reflection	Max Wave Height Near Wall	Water Overtop
Vertical Wall (VW)	Yes	1.2 cm	Yes
GS Seawall (GS)	Yes	2 cm	Yes
FSS Seawall (FSS)	Yes	0 cm	No
CPS Seawall (CPS)	Yes	1.1 cm	No
Inclined Wall (IW)	No	0 cm	No

TABLE 2: Computer Model of Waves Hitting Seawalls with uniform triangular elements. 1.5cm x 1cm Block of Water.

Type of Seawall	Wave Reflection	Max Wave Height Near Wall	Water Overtop
VW (VW)	Yes	1.84 cm	Yes
GS Seawall (GS)	Yes	1.62 cm	Yes
FSS Seawall (FSS)	Yes	0.95 cm	No
CPS Seawall (CPS)	Yes	1.06 cm	Yes
Inclined Wall (IW)	No	0.99 cm	Yes

TABLE 3: Physical experiment using the digital hydraulic bench with 2.9cm water level.

Type of Seawall	Wave Reflection	Max Wave Height Near Wall	Water Overtop
VW (VW)	Yes	12.7 cm	Yes
GS Seawall (GS)	Yes	11.4 cm	Yes
FSS Seawall (FSS)	Yes	8.9 cm	Yes
CPS Seawall (CPS)	Yes	6 cm	Yes
Inclined Wall (IW)	Yes	5 cm	Yes

Frame 3 of Figure 9 shows the reflection of the wave after hitting the seawall; a reaction that is similar to our computer simulation.

Experiments with the vertical wall were consistent with Sundar and Anand's study as we observed that waves hitting a VW are capable of amplitudes more than triple in physical experiments. While pressure was not observed during our physical experiments, computer models revealed that the VW experiences maximum pressure values at its bottom left corner; this is where the wave first impacts the VW prior to being launched into the air. Pressure at the bottom left base of the VW seawall will most likely promote scour leading to structural instability [14]. We observed that the GS seawall was an attempt at addressing seawall scour as it redirected waves away from the base of the seawall, but experienced similar amounts of water overtopping as the VW seawall due to the lack of a recurve area.

The inclined wall also behaved in a similar manner to that of our computer simulations, with the exception that waves were being reflected. The discrepancy of wave reflection for the IW is most likely due to our computer simulations' 11 second run time. Wave reflection would have most likely been observed had we designed our computer simulations' to run for a longer amount of time.

The CPS and FSS seawalls were observed to be the most effective at minimizing wave height near the seawall and at preventing water from overtopping during our physical experiments. Wave overtopping was observed with all seawalls. This is in contrast to our computer simulation where the FSS seawall was able to prevent wave overtopping. This discrepancy between our computer simulations and physical experiments is due to our method of producing waves in the latter. The DGH is unable to recreate the single wave that we used in our computer simulations. It would be ideal to have our computer simulations produce waves in the same manner as our physical experiment as waves occur continuously and not in a singular fashion. Further, our physical experiment was also capturing the interplay between multiple waves bouncing of the wave generator which resulted in waves with various heights.

5 Conclusions

Results from our computer simulations suggest that the FSS seawall is best at reflecting wave energy away from the seawall while managing the pressure from the waves by distributing it evenly throughout its curved surface. Results from our physical experiment suggest that the CPS seawall is best at reflecting waves and minimizing wave height, but did not capture any data on pressure. Both physical experiments and computer simulations point towards a need for wave energy management as the VW experiences the highest wave when hit by a wave and allows for water to go up and over the top of the seawall. Numerical and

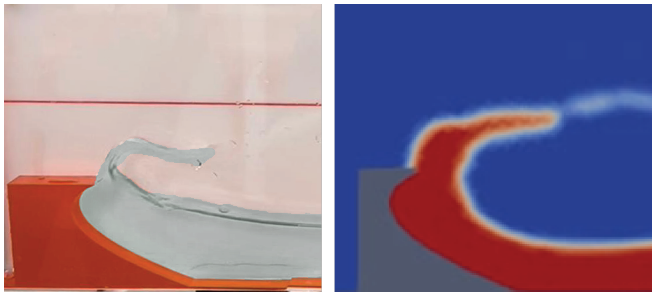


FIGURE 8: Physical experiment with CPS seawall (left) & Computer Simulation of the CPS seawall (right), with incoming waves from the right. Seawalls were proportionally scaled during tests.

physical simulations of waves hitting a VW revealed that water can reach heights more than triple that of the VW. Keeping in mind that the VW represents a simplification of situation seen in Figure 2, we predict that more water will be able to jump over the VW onto Beach Road causing Beach Road to be flooded as sea levels rise or as typhoons momentarily increase sea levels.

6 Discussion and Future Work

The main focus of our work during this project was to analyze wave reflection and potential pressure points on the face of our selected seawalls. Another focus of our project was to reproduce fluid behavior from Sundar and Anand's study [14] and confirm which seawall amongst the five in our study was best suited for reflecting wave energy. Our last goal was to create a CFD model that could accurately model fluid behavior in physical experiments. We were able to accomplish all of our goals.

The research team was able to model each of our five seawalls and confirmed that fluid behavior was acceptable when compared to their physical experiment counterparts. While some computer simulations produced results that were counter to our initial hypothesis, we kept those results as our model's goal was not to produce CFD models that are an exact copy of what would happen in reality, but rather to give the researchers an intuition to fluid behavior and suggest next steps in our research. Future work would include further refinement of our time-step and mesh in order to resolve any confidence issues pertaining to our simulations. We plan to focus on the FSS seawall in future work.

Sundar and Anand's study [14] had two main takeaways that were relevant to our research. The first takeaway was that the model-CPS seawall experienced high pressure at the recurve area when hit with a wave. We were able to observe pressure through our computer model by monitoring pressure values during the simulation and noting where it spiked as the water column moved along in the simulation. The second important aspect of Sundar and Anand's research was that a VW is a poor seawall as it could cause wave height to be more than double that of the height of the seawall itself [14]. This was true in our case, as we observed maximum wave height to be more than triple the seawall height in our physical experiments as seen in Table 3 and nearly double in our computer models as seen in Table 2. This means that the current state of Saipan's coastline, as seen in Figure 2, would be insufficient at stopping waves in the event that the Marianas experiences another typhoon or the inevitable rise in sea level.

While this study is an important first step, we plan to further our research to provide information to local stakeholders on how a seawall should be built. Further work is needed to determine if curved seawalls will result in seawall scour, the erosion of the sediment at a seawall's base due to the waves that would be reflected off the seawall. Further, as Saipan's coastline is not a straight edge, waves being reflected from one side of the Saipan coastline may have the potential to reach another side of the coastline.

Further simulations and experiments are needed to determine how waves react with seawalls using a better representation of Saipan's shoreline. Additionally, we plan to account for the change from deep to shallow water waves and the lagoon's bathymetry. Our research team is also planning to determine the optimal physical dimensions and placement of seawalls based on the waves that are currently common in the Saipan lagoon while also accounting for future effects of climate change.

ACKNOWLEDGMENT

Special thanks to the faculty at the UW Tacoma Mathematics department for their help and support, particularly Dr. J. Quinn. Thanks to Troy Dunmire and Jace Shirreff for assisting with the experimental work. We would like to also thank Pacific Northwest National Laboratory's Salish Sea Modeling Center for their support and collaboration in utilizing HYAK. Thank you, Tarang Khangaonkar Ph.D., Su Kyong Yun, and Adi Nugraha. Thank you to Cheryl Greengrove Ph.D. and Robbie Greene for initial guidance and support. Special thank you to Franco Reymund Carlos and Rory Weseloh for their peer review and research assistance in furthering this study. Thank you to Shenille Pua and Tomika Pua-Yagi for their constant support.

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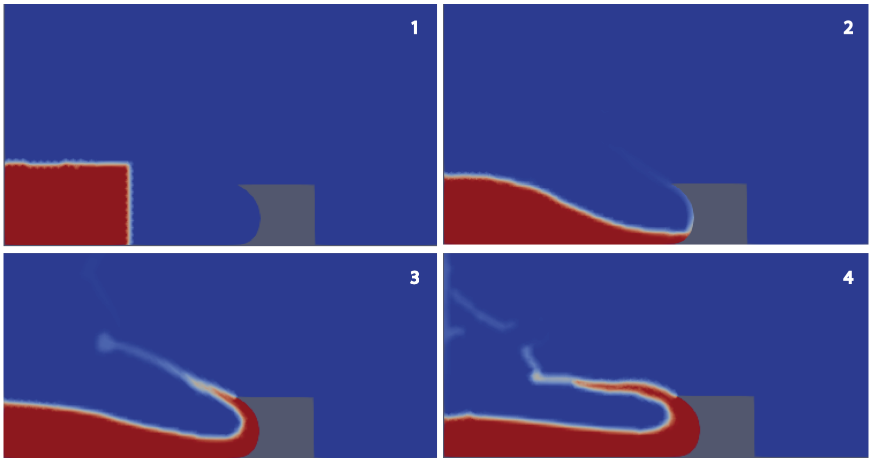

FIGURE 9: Simulating a wall of wave hitting the FSS Seawall in OpenFOAM. Wave was generated using a column of water with dimensions that are 1.5cm × 1cm. Notice that the water (red) in frames 3 and 4 reflects the incoming wave in a manner similar to frame 3 of Figure 10.

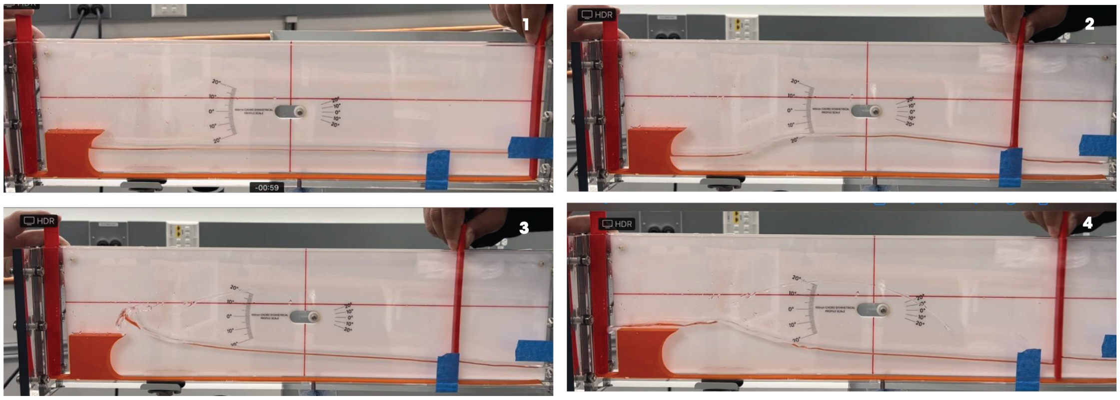

FIGURE 10: Wave hitting the FSS Seawall and subsequently reflected. Wave was generated under high velocity and high water level.

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