Protecting Shorelines with Triply Periodic Minimal Surface Inspired Breakwaters

Alex Yang
Eleanor Roosevelt High School
New York City, USA
alexy47@nycstudents.net

Michael Wen
Eleanor Roosevelt High School
New York City, USA
michaelw335@nycstudents.net

***Abstract*—Breakwaters have been used for millennia to reduce wave impact. Breakwaters are coastal structures that aim to disrupt waves by reducing their wave energy, and their abrasive impact on the shoreline. The force generated from waves gradually eroded shorelines. Breakwater designs have remained relatively static, with many breakwaters comprising mound or wall-based configurations. This study aims to innovate existing breakwater architecture by exploring the use of Triply Periodic Minimal Surfaces (TPMS) structures as breakwaters. TPMS shapes are three-dimensional periodic manifolds chosen for their mathematical simplicity, mechanical strength, and cost effectiveness. This research employs Computational Fluid Dynamics (CFD) simulation methods to explore the effectiveness of different TPMS structures in reducing the amplitude and group velocity of incoming waves. The effectiveness of each structure is compared with other TPMS structures with modified design parameters as well as with certain traditional breakwater designs with identical height and volume, namely a commonly deployed lattice design. OpenFoam software is used as the primary computational tool to simulate wave impact with OlaFlow being the primary solver. MSLattice is employed in the creation of TPMS structures. This investigation aims to explore the feasibility of TPMS breakwater and give rise to a new generation of breakwater architecture incorporating TPMS structures.**

***Keywords*—breakwater, minimal surface,**

I. INTRODUCTION

Breakwaters are offshore structures that help to protect coastlines from coastal erosion. They have become increasingly important among coastal communities to mitigate effects of rising sea levels. Various breakwater designs such as vertical walls, lattice structures, and rubble-mound breakwaters help protect shorelines globally. Minimal Surfaces (MS) are a family of mathematical surfaces which locally minimize surface area. MS are commonly formed using soapy water and wireframes.

Triply Periodic Minimal Surfaces (TPMS) are special types of MS which experience periodicity in three dimensions. This study measures the effectiveness of TPMS–based breakwater designs by comparing them against traditional structures. The performance of different types of TPMSs with various design parameters, specifically those with graded density, are also investigated.

II. BACKGROUND

TPMSs are a large family of surfaces with varied symmetries. Some have been the focus of multiple studies concerning their capacity for heat dissipation, sound absorption and stress distribution with applications in heat sinks, sound isolation and artificial bones. TPMS architectures selected for this study include Gyroid, Diamond, F-RD, and IWP. Two types of traditional breakwaters, solid wall and lattice structure, are analyzed and compared with TPMS designs. The Lattice structure represents a traditional (non-TPMS) breakwater design, while the solid wall serves as a control group as well as a datum (Fig. 1).

FIG I. BREAKWATER ARCHITECTURES

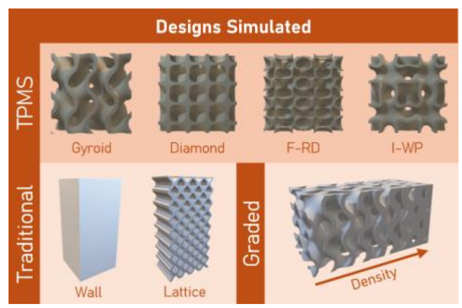

Fig. 1. Designs tested in the study.

Using the principles of linear wave theory [1], it can be shown that the mean energy flux per unit surface length of the wave (P) is proportional to the product of square of wave height (H) and wave phase velocity (c_p).

$$P = \frac{1}{8}\gamma H^2 c_g \quad \Rightarrow \quad P \propto H^2 c_g$$
$$c_g = n c_p$$
$$c_g \propto c_p \quad \Rightarrow \quad \boxed{P \propto H^2 c_p}$$

P = mean energy flux per unit surface length
γ = specific weight of water
H = wave height (double the amplitude)
c_g = wave group velocity
c_p = wave phase velocity (velocity of wave crest)
n = constant that depends on wavelength and mean water depth

Three metrics of the breakwater designs that may suggest wave dissipation efficiency are: the relative wave height reduction ($\Delta H_{\%}$), the relative wave velocity decrease ($\Delta c_{\%}$), and the drag force against the structure. Drag can also be used as a measure of structural stress and therefore structural durability. Based on the above discussion, relative energy flux decrease ($\Delta P_{\%}$) can also be used as a unifying metric for $\Delta H_{\%}$ and $\Delta c_{\%}$ to measure dissipation efficiency. Due to the proportionality relationship, $\Delta P_{\%}$ can be calculated using the equation:

$$\Delta P_{\%} = 1 - (1 - \Delta c_{\%})(1 - \Delta H_{\%})^2$$

III. METHODOLOGY

Uniform and graded TPMS designs were created using MSLattice [3]. All non-graded TPMS models have the same relative densities and volume. Graded models were created with density gradients ranging from 5%-25% to 15%-15%. Openfoam and Olaflow [4] were used for CFD simulation. A numeric wave tank was created for testing various breakwater structures. The simulation time was around 2 days for each case. The output data was imported into Paraview and extracted over three equidistant lines on two parallel planes each before and after the breakwater to measure the wave heights and wave velocity at each line (Fig. 2). The data was output into CSV files.

FIG II. DATA EXTRACTION

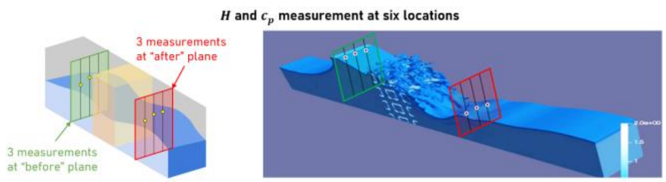

Fig. 2. Data extraction planes. Wave data are measured at yellow points..

Using Python and external modules including Matplotlib, SciPy, and NumPy, the output data were directly extracted from the CSVs. $\Delta H_{\%}$ and $\Delta c_{\%}$ for each structure was calculated by taking the average percent decrease of height/velocity peaks as the waves passed through the structure.

IV. RESULTS

The wave heights and velocities for all four types of TPMSs and Lattice structure were plotted, and the percentages of reduction are shown. Lattice seems to not have decreased the velocity to the same degree as all other TPMS structures have, and the lattice experienced less drag (Fig. 3). The tested graded Diamond TPMS designs all decreased $\Delta H_{\%}$ and $\Delta c_{\%}$ more than the Uniform Diamond structure (Fig 4).

FIG III. UNIFORM STRUCTURE METRICS

Design	Wave Decrease Metrics		
	$\Delta H_{\%}$	$\Delta c_{\%}$	$\Delta P_{\%}$
Lattice	38.65	28.41	72.98
Diamond	46.07	66.69	90.31
I-WP	44.99	53.84	86.03
Gyroid	45.04	61.72	88.44
F-RD	62.61	75.21	96.53

FIG IV. GRADED STRUCTURE METRICS

Density Gradient	$\Delta H_{\%}$ and $\Delta c_{\%}$ for Graded TPMS	
	$\Delta H_{\%}$	$\Delta c_{\%}$
5%-25%	48.36	76.77
10%-20%	46.78	75.85
15%-15%	46.47	75.79
20%-10%	47.08	76.17
25%-5%	47.41	75.14

Lattice experienced the lowest drag, with a relative drag of 0.2360. The TPMS designs of Gyroid, Diamond, and I-WP structures show impressive drag decrease relative to a wall with the same dimensions (Fig. 5).

FIG V. MAXIMUM DRAG FOR VARIOUS STRUCTURES

Design	Drag	
	Maximum Drag (N)	***Relative Drag (Wall=1)***
Lattice	11,604	0.2360
Diamond	30,587	0.6220
I-WP	31,660	0.6438
Gyroid	30,509	0.6204
F-RD	35,077	0.7133
Wall	49,175	1

All tested TPMS designs have greater $\Delta H_{\%}$ and $\Delta c_{\%}$ than the Lattice structure, implying that TPMS designs are more effective at reducing the P of waves. Some TPMS structures also take in higher drag forces compared to Lattice; However, they

TPMS demonstrate impressive drag reduction with respect to a wall with identical dimensions. Similarly, the graded Diamond designs performed better in wave reduction than the non-graded Diamond design. F-RD seems to be the most effective TPMS design tested for wave reduction due to the maximal $\Delta P_{\%}$ metric at 96.53%. Diamond seems to be the most effective TPMS structure for breakwater use considering its $\Delta P_{\%}$ is only 6.22% less F-RD with respect to the wall and reduces drag by 9.13% with respect to the wall. Graded versions of Diamond also, in general, are more efficient at wave reduction than uniform versions.

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