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BARRIER: Breakwater and Resilient Response for Infrastructure Erosion Reduction: A Coastline Protection Plan for Sitio Delta, Consuelo, Macabebe, Pampanga

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Abstract:

Coastal areas play a critical role in protecting communities from natural disasters, yet rapid coastal erosion is reshaping these environments, endangering both the coastlines and the communities dependent on them. The coastline of Sitio Delta in Consuelo, Macabebe, Pampanga, is particularly vulnerable due to its proximity to Manila Bay, resulting in frequent flooding during heavy rains and typhoons. To address these risks, the researchers proposed the design of a concrete breakwater system aimed at mitigating wave impacts and preventing further coastal erosion. The objective of this research is to analyze the hydrodynamic conditions affecting the study area and develop an effective breakwater system to safeguard the coastline. The data necessary to determine the height, width, and other important parameters of the structure were gathered from PAGASA and other open- source platforms. Additionally, OpenFOAM, an open-source simulation software, was used to model the performance of the breakwater system in preventing coastal erosion. The structural stability and resilience of the proposed breakwater were evaluated using established equations developed by Goda.

Keywords **— coastal erosion, breakwater, hydrodynamic conditions, OpenFoam, Goda.**

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I. INTRODUCTION

Coastal erosion, often called the "silent killer," is a gradually intensifying threat that impacts both natural ecosystems and human settlements. With nearly 40% of the global population living along coastlines, the steady loss of land due to wind, waves, typhoons, and climate change presents severe ecological, economic, and social challenges (U.N. Environment, 2017). These natural forces not only reshape coastlines but also destabilize soil, increase flood risks, and endanger infrastructure in vulnerable, low-lying areas (Luque et al., 2021).

Sitio Delta, a purok located in Barangay Consuelo, Macabebe, Pampanga, is facing a critical coastal risk that threaten its very existence. The proximity of the area to the Manila Bay makes it highly susceptible to erosion. The erosion of shorelines threatens local livelihoods, biodiversity, and the long-term sustainability of communities. Traditional erosion control methods like retaining walls often prove inadequate against strong and continuous wave energy, leading to high maintenance demands and limited resilience (Bernarte et al., 2023).

Breakwater systems, in contrast, offer a more effective and sustainable coastal defense. By reducing wave energy offshore, they help preserve shoreline integrity and protect infrastructure with less frequent maintenance. Their role aligns with Sustainable Development Goals (SDGs), particularly SDG 9 on resilient infrastructure and SDG 13 on climate adaptation.

As sea levels rise and extreme weather events become more common, the urgency to implement reliable, long-term solutions becomes clear. Investing in sustainable coastal protection, such as breakwaters, is essential to safeguarding coastlines, ecosystems, and the communities that depend on them before irreversible damage occurs.

This study aimed to design and analyzed an effective breakwater system to mitigate wave-induced coastal erosion along the shoreline of Sitio Delta, Barangay Consuelo, Macabebe, Pampanga. The study encompassed specific objectives such as investigating the influence of local wind and hydrodynamic conditions in the area using OpenFOAM software, defining key geometric dimensions for the breakwater design, and determining the optimal design parameters to ensure structural stability through numerical modeling and analysis.

II. METHODOLOGY

Figure 1 illustrates the phases of the study methodology used to achieve the objectives and results of the study. Phase 1 involves the evaluation of design variables, where key parameters that influence the coastal erosion will be identified. Phase 2 focuses on designing the breakwater system itself. This involves integrating the evaluated design variables to create a model that meets the study's objectives. The final phase, Phase 3, entails analysis through simulation, utilizing software tools such as OpenFOAM and ParaView. In this stage, the designed breakwater system will be subjected to various simulations to assess its performance under different conditions.

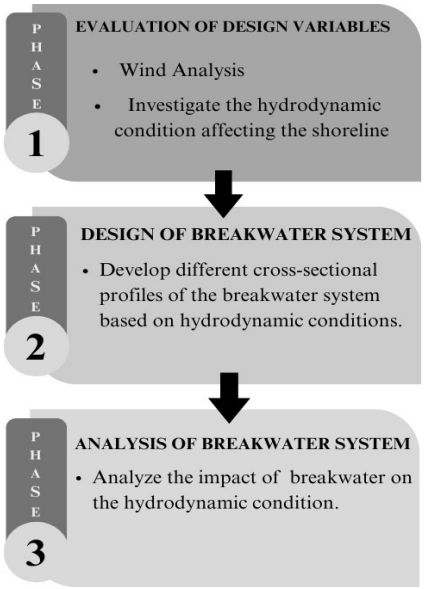

Figure 1. Methodological Framework

A. Evaluation of Design Variables

The first method presented a simulation-based approach for designing coastal protection structures, particularly in assessing the effects of hydrodynamics in the coastal region of Sitio Delta, Barangay Consuelo, Macabebe, Pampanga. The process involved evaluating environmental variables, analyzing the collected data to understand the coastal conditions, and simulating the system's performance using OpenFOAM.

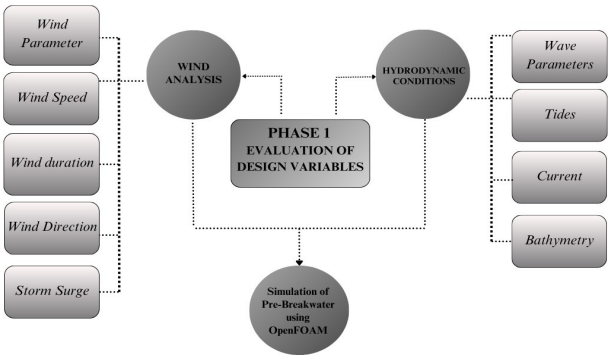

Figure 2. Phase 1 Flow Diagram

Key coastal factors such as wind, waves, tides, sea-level pressure, temperature, and bathymetry were thoroughly analyzed. Wind data were obtained from PAGASA and Copernicus Marine Services. Wave characteristics including height, direction, and period sourced from Copernicus Marine as well. These datasets were used to understand coastal dynamics and assess the forces acting on the shoreline. Tides and atmospheric pressure were studied due to their roles in storm surges and wave amplification, while bathymetric information helped define the seabed's shape for accurate modeling.

Based on this environmental assessment, the study aimed to identify the effects of coastal conditions on erosion. The maximum data collected was used to design a structure capable of withstanding both typical sea conditions and extreme events such as typhoons. This helped identify the current condition of the coastline in the absence of any breakwater in the area,

To evaluate the design's effectiveness, simulations were conducted using OpenFOAM, a software tool for modeling fluid dynamics. It enabled the visualization of wave movement and interaction with the breakwater. The Reynolds-Averaged Navier-Stokes (RANS) equations, along with turbulence models, were applied to simulate realistic wave impacts. The results were compared to real-world data to ensure accuracy.

To assess the situation, the table below presents the impact of pressure on coastal erosion based on the simulation results.

Table 1: Wave Impact Pressure and Coastal Erosion Risk Reference

Wave Pressure (kPa)	Wave Type Condition	Wave Height (H)	Erosion Risk	Reference
< 10 kPa	Non-breaking, gentle swell	< 1.5 m	Very Low	Goda (2000). Hughes (1993)
10–50 kPa	Regular waves, moderate sea	1–2.5 m	Low to Moderate	Goda (2000)
50–100 kPa	Spilling breakers, small storms	2–4 m	Moderate to High	Goda (2000); USACE CEM (2002)
100–300 kPa	Plunging breakers, strong storms	3–6 m	High to Very High	Goda (2000). Yehetal. (2005)
> 300 kPa	Extreme events	> 6 m	Severe/ Catastrophic	Yehetal. (2005). Coastal case studies

This approach demonstrated that combining environmental data with advanced simulation provided a reliable way to design and assess coastal defenses in erosion-prone areas.

B. Design of a Breakwater System

Phase 2, as shown in figure 3, involved the mathematical design of the breakwater, focusing on determining its optimal dimensions. It combined analytical calculations with advanced visualization to ensure the design could effectively resist hydrodynamic forces.

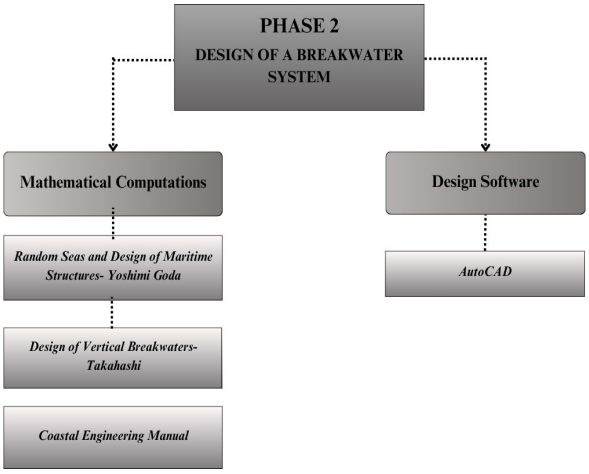

Figure 3. Phase 2 Flow Diagram

B.1. Mathematical Computations

Following the assessment of hydrodynamic conditions in Sitio Delta, Consuelo, Macabebe, Pampanga, the collected data served as a basis for designing an effective breakwater system aimed at reducing coastal erosion and improving shoreline stability. Key references for the design and computation of parameters as shown in figure 4 included *Random Seas and Design of Maritime Structure* by Yoshimi Goda, *Design of Vertical Breakwaters* by Takahashi, and the *Coastal Engineering Manual.*

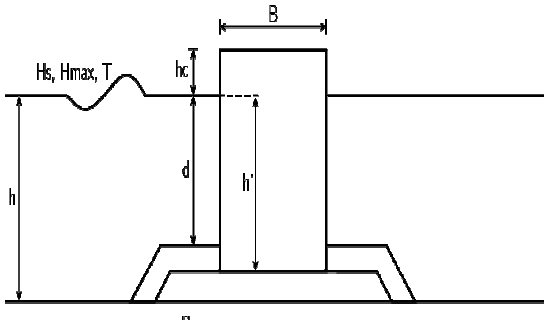

Figure 4.: Parameters in the Extended Goda Formula

B.1.1. Design of Breakwater Height

Calculations for this portion were computed according to Coastal Engineering Manual- Chapter VI-1110-1100, EuroTop Chapter VI

First, a simplified method, equation 5.60 in TRM, was used to determine the minimum breakwater height required to limit wave transmission, to 10%. A ^{h_c} value of 1.2 was used.

$$1.2 \leq \frac{h_c}{H_s} < 2.0$$
$$C_T = 0.10$$
$$h_c = 1.2H_s$$

Freeboard, *hc* is the value which must be added to the water depth to determine the total height of breakwater. Therefore:

$$H_T = h_c + h$$

B.1.2. Design of Breakwater Crest

According to the Coastal Engineering Manual (1999) in a harbor where the water area behind the breakwater is so wide that the wave overtopping can be allowed to some extent, the crest elevations of the breakwaters is set 0.6 times significant wave height $\frac{H_1}{3}$ above highest water level (*h*)

$$B' = h + 0.6H_s$$

B.1.3. Design of Breakwater Base

According to Coastal Engineering Manual (1999), the bottom width of a breakwater can be calculated using the formula of

$$B = B' + 2H_T$$

This formula assumes a trapezoidal cross-section with a side slope of 1H:2V, which is a common design for stable breakwater.

Table 2: Wave Parameters Formula

DESIGN PARAMETERS				
Parameters	Symbol	Definition	Formula	Unit
Wave Height	H_s	mean of the waves of the highest 1/3 of the wave heights	$\frac{1}{(\frac{N}{3})}\sum_{i=1}^{\frac{N}{3}} Hi$	M
Design Wave Height	H_{max}	mean of the highest 1/250 of the wave heights	$\frac{1}{(\frac{N}{250})}\sum_{i=1}^{\frac{N}{250}} Hi$	M
Water Depth	h			M
Water Depth on Top of Foundation	d	water depth from the top of the foundation to the sea surface		M
Submerged Depth of the Caisson	h'	from SWL to the bottom of the caisson		M
Freeboard	h_c	height of the vertical breakwater above SWL		M
Wave Period	T		$\frac{T}{3}$	S
Beta	β	angle between direction of wave approach and a line normal to the breakwater		rad or deg
Density	ρ	density of sea water		kg/m^3
Crest Width	B'	top surface width of the breakwater	refer to Coastal Engineering Manual	M
Base Width	B	bottom surface width of the breakwater	refer to Coastal Engineering Manual	M
Total Height of Breakwater	H_T	height of breakwater from the bottom to the top surface	refer to Coastal Engineering Manual	M

B.2. Software and Functions AutoCAD

AutoCAD was used to generate breakwater design, illustrating key features such as height, width, slope, and form. This allowed for visualization, alignment, and adjustment based on engineering and hydrodynamic requirements. Figure 5 to 7 show sample 3D visualizations of the system.

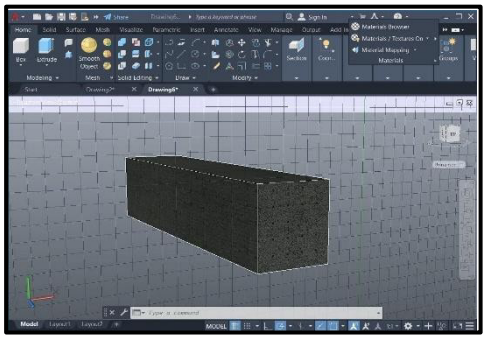

Figure 5. Breakwater System with Square Cross Section

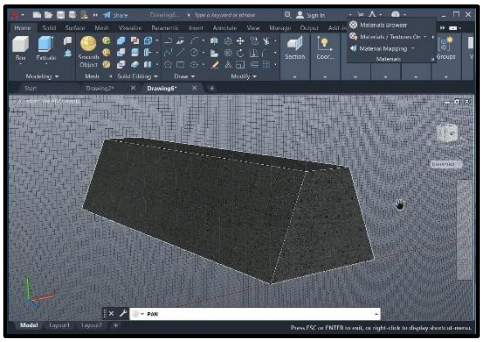

Figure 6. Breakwater System with Trapezoidal Cross Section (two face slopes)

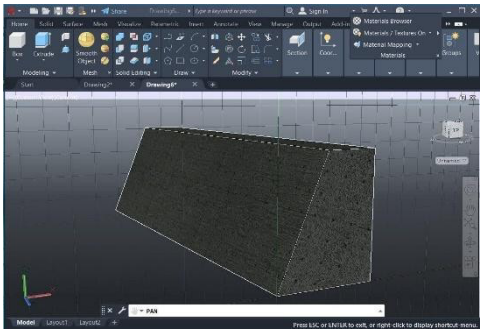

Figure 7. Breakwater System with Trapezoidal Cross Section (single face slopes)

III. RESULTS AND DISCUSIION

To evaluate and comprehend the performance of various sections of breakwaters under identical wave conditions, three cross-sections were analyzed, a conventional vertical breakwater, a one-sided sloped trapezoidal breakwater and two-sided sloped vertical breakwater. These configurations have been selected to investigate how different structural modifications influence key hydrodynamic parameters.

C. Analysis of Breakwater System

The Phase 3 of the breakwater system analysis, as illustrated in Figure 8., which focuses on evaluating the effectiveness of breakwater structures under varying hydrodynamic conditions. The analysis is divided into three distinct stages involving simulation, post-processing, and structural assessment.

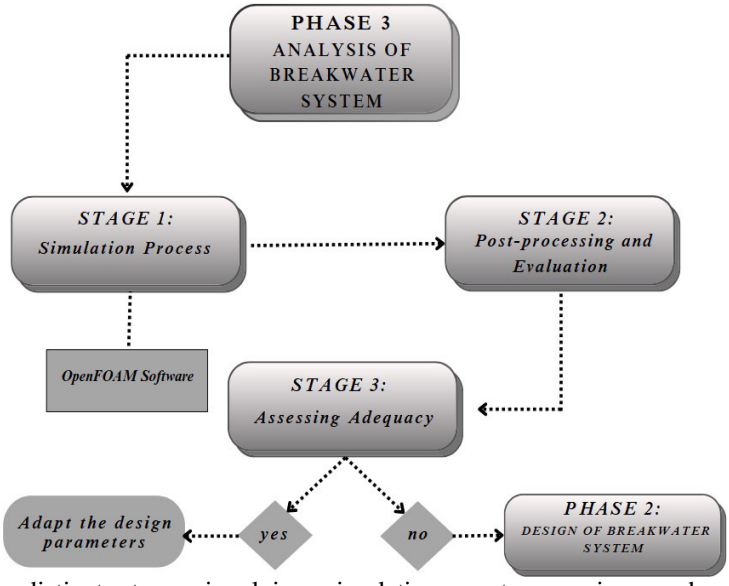

Figure 8. Phase 3 Flow Diagram

STAGE 1: *Integration with OpenFOAM*

In the first stage, simulations are conducted using OpenFOAM, a computational fluid dynamics (CFD) tool. OpenFOAM facilitates advanced numerical modeling to simulate the interaction between waves and breakwater structures, providing insights into their ability to reduce wave energy and protect coastlines. The simulations incorporate either two-dimensional (2D) or three-dimensional (3D) numerical channels within a defined computational domain that replicates real coastal conditions, including anticipated wave characteristics.

The design of the breakwater generated through CAD software is imported into OpenFOAM where a computational mesh is constructed. The mesh resolution is critical for accurately capturing fluid dynamics. Material properties such as concrete density and compressive strength are incorporated to ensure realistic interaction with water. The simulations are governed by the Navier–Stokes equations, appropriate for modeling the incompressible behavior of water. Appropriate boundary conditions, such as non- slip surfaces, wave generation, and wave absorption zones, are applied.

To quantify the Project BARRIER effectiveness, the simulation compares wave pressure distributions before and after the breakwater installation. This enables the evaluation of wave energy dissipation, and the protection offered to the leeward side. The simulation also examines how geometric variations in height, slope, and width affect structural response to hydrodynamic forces, guiding potential design modifications.

STAGE 2: *Post-processing and Evaluation*

The second stage involves post-processing and evaluation of simulation outputs. OpenFOAM generates time-based field data files containing vector quantities such as wave velocity and pressure. These outputs are analyzed using ParaView, a visualization software that assists in interpreting flow dynamics, wave patterns, and potential structural failure zones. Derived quantities, including flow rates and energy balances across the domain, are used to assess the design's effectiveness. Comparisons of wave heights before and after the breakwater structure are employed to gauge energy attenuation. In addition to pressure analysis, wave run-up and overtopping are also examined. Run-up height refers to the maximum vertical extent of wave uprush on the breakwater, while overtopping volume indicates the amount of water surpassing the crest under given conditions. These parameters are vital for assessing the structure's resilience to extreme hydrodynamic events.

STAGE 3: *Assessing the Adequacy of Breakwater System*

The third and final stage assesses the structural adequacy of the breakwater system by calculating sliding and overturning moments, which are essential for ensuring stability under wave forces. The upright portion of the breakwater must demonstrate sufficient resistance to both sliding and overturning. Using formulations from Yoshimi Goda's "Random Seas and Design of Maritime Structures," safety factors are evaluated under both static and dynamic conditions.

Static Condition

$$Against\ Sliding: SF_s = \frac{\mu R_y}{R_x} > 1$$

$$Against\ Overturning: SF_o = \frac{RM}{OM} > 1$$

Dynamic Condition

$$Against\ Sliding: SF_s = \frac{\mu(W_o - U)}{P} > 1.2$$

$$Against\ Overturning: SF_o = \frac{W_o t - M_u}{M_p} > 1.2$$

Where:

μ = denotes the coefficient of friction between the upright section

W_o = weight of the upright section per unit extension in still water U = total uplift force per unit extension

P = the total horizontal wave force per unit extension

t = the horizontal distance between the center of gravity and the heel of the upright section

M_u = the uplift moment around the heel of the upright section

M_p = the moment due to the horizontal pressure around the heel of the upright section

III. RESULTS AND DISCUSSION

The results and discussion focus on the results and analysis of the proposed breakwater system for Sitio Delta, Brgy. Consuelo, Macabebe, Pampanga. It begins with the assessment of the hydrodynamic conditions and wave analysis where wave behavior, bathymetry, tides and meteorological influences were studied to understand the site's vulnerability. The simulations used waved data sourced from 1993 to 2025.

Table 3.: Maximum values of environmental forcing parameters from the 1993 to 2025 dataset used in the simulation.

Variables	Value
Max Wind Speed	4 m/s
Max Wind Direction	360 degree
Rainfall	945 mm
Max Sea Temperature	36.4 °C
Surface Pressure	100.3 kPa
Mean Sea Level Pressure	101.7 kPa
Significant Height of Combine Wind-wave and Swell	4.1 m
Wave Direction	360 degree true north
Wave Duration	11.1 s

Using OpenFOAM software, it was modeled three types of breakwaters: vertical, single- sloped, and double-sloped, based on Goda's empirical formulas. The rectangular cross-section design measured 8.5 m in height and 6.5 m base width. The single-sloped design had a 8.5 m height, 6.5 m base width, and 17 m crest width, while the double-sloped type featured similar dimensions but with a symmetrical crest width structure of 6.375 m.

Table 3.2: Performance Comparison of Breakwater Types

Performance Indicator	Rectangular	Single-Sloped	Double-Sloped
Seaward Face Pressure (kPa)	80.582	79.966	71.288
Shoreline Pressure (kPa)	48.468	48.469	48.471
Wave Height Reduction (%)	60.47	62.79	62.79
Total Pressure received of the Dike (kPa)	68.676	68.677	68.679
Factor of Safety against Overturning under Static Condition	4.51	4.096	3.44

Factor of Safety Against Sliding under Dynamic Condition,	0.820	1.567	1.489
Factor of Safety Against Overturning under Dynamic Condition,	3.920	10.170	23.240

The single-sloped breakwater was the selected design because the optimal solution due to its economical, structural stability and wave energy dissipation. This design is recommended to safeguard Sitio Delta, Brgy. Consuelo, Macabebe, Pampanga against ongoing coastal erosion and climate driven wave activity.

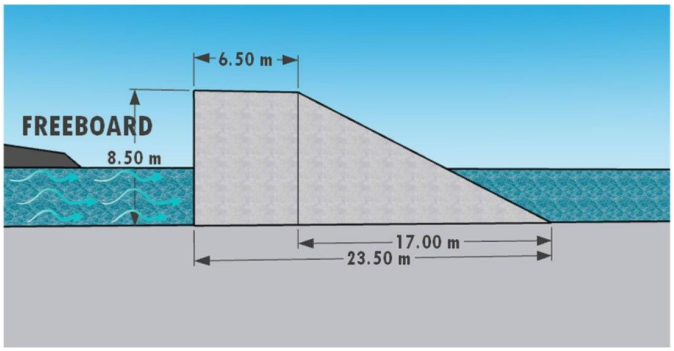

Figure 9: Single-Sloped as the optimized design of breakwater

IV. Conclusion and Recommendations

A. Conclusion

Project BARRIER provided insights into developing a coastal protection plan for Sitio Delta, Consuelo, Macabebe, Pampanga. After evaluating three breakwater designs, the one-sided sloped breakwater performed best in reducing wave energy, minimizing wave overtopping, and efficiently dissipating dynamic pressure. It met the required safety standards and showed strong stability against sliding and overturning. These results confirmed that one-sided sloped breakwater is an effective design for protecting the shoreline and coastal infrastructure. The design is expected to help control erosion and provide long-term coastal resilience.

B. Recommendations

The following actions are recommended to ensure the success and durability of the breakwater:

- Conduct geotechnical assessment to evaluate foundation stability and soil-structure interaction at the project site
- Include sediment transport analysis to predict scouring, sediment build-up, and shoreline changes that may affect the structure over time.
- Test the durability of concrete materials under marine conditions to ensure resistance to saltwater exposure, temperature changes, and weather variations.
- Review construction feasibility based on local material availability, cost, and practical construction methods to ensure the project can be implemented effectively in Sitio Delta, Consuelo, Macabebe, Pampanga.

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We are grateful to the local officials of Barangay Consuelo, Macabebe, Pampanga and the office of Municipal Disaster Risk Reduction Management in Macabebe, Pampanga, for their warm accommodation, local knowledge, and provision of background information related to community needs, historical data and ongoing coastal issues. Their input helped shape the practical relevance of our design.

We would also like to recognize the collaboration and individual efforts of each group member. From data collection, simulation, and analysis to design development and documentation, every task was a collective product of dedication, cooperation, and problem-solving under time constraints. The distribution of work was thoughtfully managed to reflect the strengths and skills of each member, resulting in a well-rounded and technically sound output.

To our fellow students, friends and research peers who provided feedback during our proposal presentations and dry runs, your suggestions greatly contributed to the clarity and quality of our final work.

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