INSPIRE FELLOWSHIP

PROGRESS REPORT

1. **Name of the INSPIRE Fellow:** SANTANU KUMAR DASH

2. **Nature of Fellowship (JRF /JRF-Professional /SRF):** JRF

3. **INSPIRE Fellowship Code No. :** IF200487

4. **Name, Designation and address of the Guide:**
   Prof. Santanu Koley,
   Associate Professor,
   Department of Mathematics,
   Birla Institute of Technology and Science-Pilani, Hyderabad Campus,
   Hyderabad, Telangana - 500078

5. **a) Place of Work (Name of the Institute /University/ College etc):**
   Birla Institute of Technology and Science-Pilani, Hyderabad Campus
   b) Name of University /institute registered for Ph.D. degree:
   Birla Institute of Technology and Science-Pilani, Hyderabad Campus

6. **Date of Joining to INSPIRE Fellowship:** 18 February, 2022

7. **Period up to which fellowship is tenable:** 17 February, 2027

8. **a) Date of Enrollment for Ph. D. Program:** 21 January 2022
   b) Date of Registration /Admission into Ph. D. program: 21 January 2022

9. **(a) Topic of research :**
   Development of Higher Order Boundary Element Method for Mathematical Modeling of Wave Energy Converter Devices
   (b) Broad Subject area : Integral Equation

10. **Objective in undertaking work :** The main objective is to develop a higher-order boundary element method-based numerical tools to study the efficiency of wave energy converter (WEC) devices in real sea conditions. Following is a list of attainable problems that will be investigated in this proposed work.

1. To develop a higher-order boundary element method to model the hydrodynamics associated with wave energy converter devices.
2. To study the performance of OWC wave energy converter devices placed over an undulating real seabed subjected to ocean currents.
3. To study the convergence of the numerical solutions obtained from the developed higher-order boundary element method.
4. To optimise various parameters to achieve maximum performance of the WEC devices.

11. Period of Report : 18 February, 2022 - 17 February, 2024.

12. Attendance :

(a) Total No. of working days during the period under report :

730 days (18 February, 2022 - 17 February, 2024)

(b) Out of these, total No. of days in which the INSPIRE Fellow was present and worked :

709 days (18 February, 2022 - 17 February, 2024)

(c) Number of days for which leave was sanctioned: 21

13. Detailed report about the research work done during the above mentioned period. This should include quantitative results of research presented in table(s) /figure(s), discussion and conclusions drawn [Limited to five A4 size page with 1.5 line space] : (See Appendix-1)

14. Summary of research work during this period (One A4 size page with 1.5 line space) : (See Appendix-2)

15. Plan of work for the next year (One A4 size page with 1.5 line space) : (See Appendix-3)

16. Research papers published /accepted for publication /communicated for publication (Maximum five best publications /communications) :

1. Dash SK, Swami KC, Trivedi K, Koley S. ”Boundary Element Method for Water Wave Interaction with Semicircular Porous Wave Barriers Placed over Stepped Seabed”. In International Conference on Mathematical Modeling and Computational Science 2023 Feb 23 (pp. 95-105). Singapore: Springer Nature Singapore.
2. Dash SK. and Koley S. 2023 “Performance of an OWC Device Under the Influence of Ocean Currents” **Communicated**.
3. Kailash Chand Swami . Santanu Kumar Dash . Santanu Koley,Scattering of Ocean Waves by Porous Membrane Type Wave Barriers Placed Over Undulated Seabed, J. Innovation Sciences and Sustainable Technologies, 3(4)(2023), 197 - 206. https://doie.org/10.0101/JISST.2024716276.
4. Dash SK., Trivedi Kshma., and Koley S. 2023 ”Modeling The hydrodynamics of OWc device in presence of Ocean Currents” **Communicated**.
5. Dash SK., and Koley S. 2024 ”Iterative boundary element method for modeling an inverted T-type porous barrier in presence of ocean currents” **Communicated**.

17. It is confirmed that I have devoted my full time to research and that I did not take up any other paid or unpaid activity without taking written permission from DST. It is also certified that due acknowledgement of DST financial assistance has been made in the published paper.

Date: February 6, 2024 **Signature of INSPIRE Fellow**

18. Overall assessment and comment of the Guide:

(a) It is certified that the information provided above and enclosed Progress Report are correct to the best of my knowledge and belief.

(b) My specific comments about the performance of the Fellow are as under:

(c) The Fellowship is recommended /not-recommended for its continuation to next year.

Date: February 6, 2024 **Signature of Ph.D. Supervisor**

Appendix-1

Report of the Research Work

(From 18th February 2022 to 17th February 2024)

Santanu Kumar Dash
Department of Mathematics. Birla Institute of Technology and Science- Pilani,
Hyderabad campus, Hyderabad-500078, Telangana, India.

This report describes the progress of my research work carried out during my JRF period from 18 February 2022 to 17 February 2023. Following with the course work, we have successfully developed a constant Boundary Element Method (BEM) for the two-dimensional elliptic-type partial differential equation by examining its mathematical foundation from the potential theory, Green's functions, and identities to Fredholm integral equations and using this, several real-life marine structure problems have been investigated. The details of the research carried out during these two years are summarized as follows:

1. Boundary Element Method for Water Wave Interaction with Semicircular Porous Wave Barriers Placed Over Stepped Seabed

In recent years, surface-piercing lightweight wave barriers for temporary protection of various marine structures have acquired considerable interest in the marine and coastal engineering field. Due to surface-piercing in nature, these lightweight wave barriers create an obstruction to the free surface ocean waves and help to mitigate the incoming ocean wave energy to a large extent. In this context, this research investigated the dispersion of water waves by inverted semi-circular surface-piercing wave barriers installed on a stepped seabed. In addition, the influence of porosity, geometrical configurations of pair of porous barriers, and stepped seabed on the energy dissipation are investigated. With the applicability of BEM, the computational domain of the physical problems is illustrated in Fig. 1. The highlights of the research are listed as follows:

- The investigation has been done by considering the small amplitude water wave theory. In this context, the governing equation, boundary conditions associated with the computational domain structure, and pair of porous boxes should follow potential theory.
- The research is fully carried out by adopting the boundary element method to analyze the hydrodynamics of the physical problems by considering several structural configurations like submergence length, with the barrier, and physical properties like the effect of porosity.
- The investigation includes the nonlinear quadratic pressure drop condition, which signifies the energy dissipation through the porous barrier and shows the applicability of BEM to handle nonlinear boundaries.
- The energy identity has been derived to check the accuracy of the computational results obtained using numerical methods. These energy identities are also used to get qualitative information about various physical quantities of interest.
- It has been noticed that energy dissipation gets lowered with an increase of KC number in the profile of short water waves, and an opposite pattern is seen in the case of long water wave profile.

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- The report also shows that as the values of KC increase, the reflection by porous barriers increases, based on the phenomenon that when the values of KC become higher, the porosity of the wave barrier decreases, and consequently the thin barriers behave as a non-porous structure.
- The findings conclude that for a suitable combination of structural and physical design, a good amount of ocean wave energy can be dissipated by this porous barrier and can act as a promising structure compared to bulky submerged breakwaters.

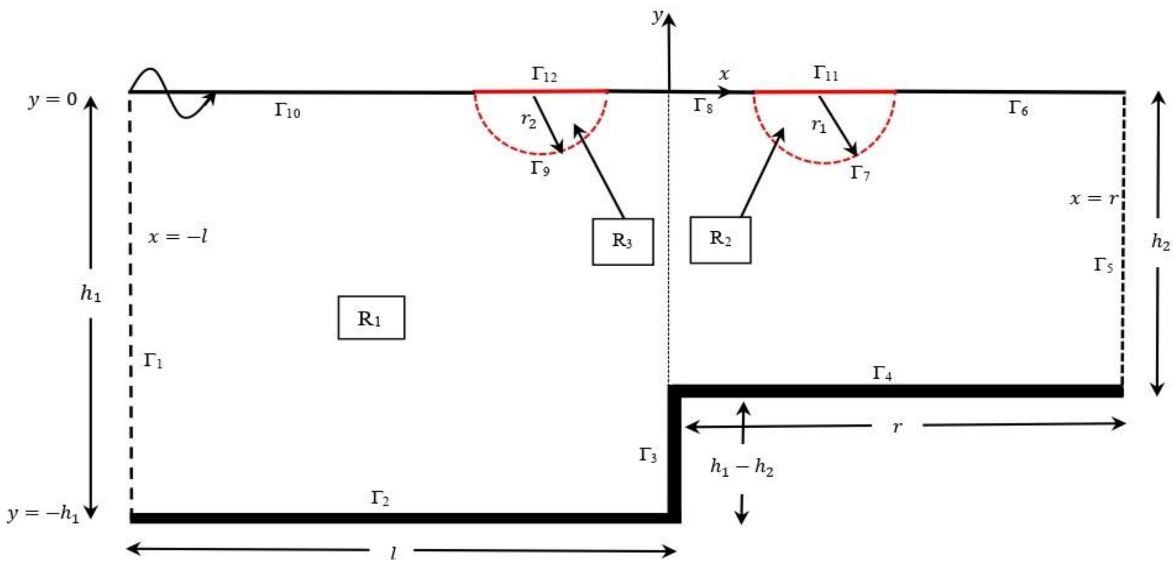

Figure 1: Schematic illustration of inverted semi-circular porous wave barriers placed over a stepped seabed.

2. Modeling the hydrodynamics of OWC Device Under the Influence of Ocean Currents

Among all the wave energy converter devices, the oscillating water column (OWC) devices are one of the key innovations that initially developed in the first decade of the nineteenth century and, therefore, frequently referred to as the first generation of devices. The OWC device consists of an open-end box comprised of concrete or steel that is partially submerged in the ocean and the Wells turbine, which is located at the top of the OWC device chamber. In the presence of incident waves, pressure oscillations arise in the water column inside the chamber. The air above the internal free surface inside the enclosed chamber is forced through the turbine by this internal pressure fluctuation, which finally drives the electrical generator to produce electricity. A large extent of research has been carried out on the hydrodynamics performance of the OWC device by considering several structural configurations, but there is no explicit research carried out when it comes to mutual wave-current interaction. In this realm, the present study explored the mathematical modeling of the hydrodynamics associated with the OWC wave energy converter device placed over the undulated seabed in the presence of ocean currents. The major assumptions and findings of the research are as follows:

- The mathematical problem is studied in the two-dimensional Cartesian coordinate system under the linearized water wave theory (see Fig. 2).
- The application of BEM application is used to handle the associated boundary value problem by properly discretizing the computational domain and implementing it into simulating software like MATLAB to get the best simulated results of various hydrodynamic factors.

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- Major emphasis is given to analyze the efficiency and horizontal wave force acting on the front wall of the OWC device for various values of incident wave and current parameters and shape parameters associated with the OWC devices and undulated seabed.
- Further, the time-domain analysis is carried out in which the free surface elevations are demonstrated for different instants of time in the presence of following and opposite currents.
- The results demonstrate that the Doppler Shift effect of the frequency due to the presence of ocean currents significantly influences the resonating patterns of the efficiency and force curves. As the current velocities increase, the resonating frequencies occur for higher values of incident wavenumbers.
- It is found that the OWC-WEC device can effectively capture and store wave energy over prolonged durations. It can be inferred that the hydrodynamic efficiency of the OWC-WEC device, when subjected to ocean currents, can be substantially improved by employing suitable combinations of shape parameters pertaining to the OWC device and undulating seabed.

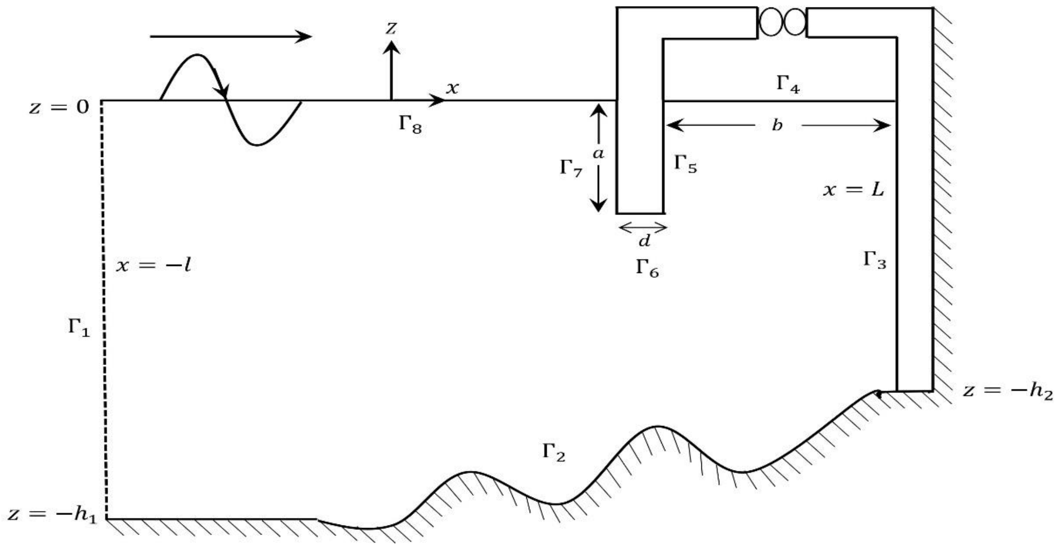

Figure 2 computational domain of OWC device placed over undulated bed.

3. Performance of an OWC Device Under the Influence of Ocean Currents

With minimal environmental impact and self-renewing characteristics, renewable energy sources have acquired considerable attention in recent years as an alternative to the combustion of fossil fuels to fulfill energy requirements for a near-sustainable future. The ocean is considered to be a vast resource of renewable energy. If explored, ocean waves and currents can provide tremendous energy and outstanding prospects for sustainable power generation. Ocean currents are not only generated by tides but also by wind, temperature, and salinity differences. They can also act as a promising sustainable energy resource because the consistent flow of water yields consistent and foreseeable energy. In this context, this work demonstrates the performance of an OWC device mounted over a uniform sea bottom in the presence of ocean currents. The idealized geometry of the computational domain for the aforementioned physical problem is depicted in Fig. 3. The key ideas and output of the research are as follows:

- The whole problem has been investigated by adopting the constant boundary element approach and to get the simulated outcomes of the problem the MATLAB software is used.

- The mutual wave current propagation is supposed to follow the potential theory, and the governing equations, along with the boundary conditions, are derived based on the small amplitude water wave theory.
- The effect of the currents propagating along the waves and against the direction of waves is analysed with the help of power absorption quantity.
- The impact of different geometrical configurations, like varying the front wall submergence depth, and chamber width, is discussed in a detailed manner. It is noticed that the influence of ocean currents in wave propagation plays a crucial role in the power absorption process through the OWC device.
- The simulated results of the aforementioned research reveal that for different values of chamber width and submergence depth, the resonance occurs. It has been also found that, for various values of the current parameter, the amplitude of the resonance rises and then gradually decays with increment in the time period. Further, it is noticed that, due to the impact of following ocean current on the OWC device, the peak in the power extraction curves increases, which ensures that a considerable amount of power can be harnessed in presence of following ocean currents

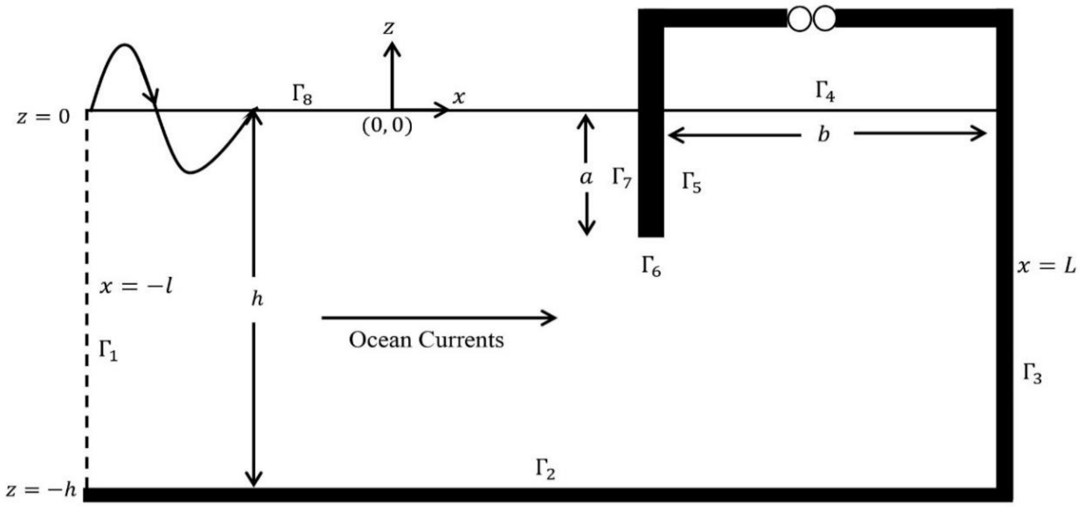

Figure 3 Schematic diagram of the OWC device placed over the uniform bottom

4. Iterative boundary element method for modeling an inverted T-type porous barrier in presence of ocean currents

The utilization of lightweight and cost-effective thin porous structures to safeguard marine infrastructure from the impact of high amplitude wave-current interaction has been a great concern in recent years. In this regard, the present study investigates the scattering of ocean wave currents by an inverted T-type lightweight surface-piercing wave barrier that is situated over a uniform sea bed. The idealized geometry for the computational domain is illustrated in Fig. 4. The major assumptions and findings of the research are summarized as follows:

- The investigation of the mutual-wave current interaction phenomena has been studied in the context of classical linear water wave theory.
- To handle the boundary value problem, accompanied by a nonlinear quadratic pressure drop boundary condition, the problem is investigated using an iterative boundary element procedure.

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- To analyze the efficacy of employing thin wave barriers, the impact of porosity, relative submergence depth, and width of the barrier on the hydrodynamic properties (like wave force, reflection, dissipation, and transmission) are investigated in the presence of ocean currents.
- The simulated outcomes demonstrate that the Doppler Shift effect of the frequency due to the presence of ocean currents significantly influences the behavior of the aforementioned hydrodynamic properties.
- The presence of the following current in the wave propagation can significantly enhance wave reflection and dissipation and decrease the transmission, whereas an opposing behavior can be found when it comes to opposing current in the case of a long wave regime.
- For higher KC values, the porosity decreases, which shows that reflection by the porous barrier is more and transmission is less, whereas the energy dissipation gets lower in the long wave regime. However, for lower KC values, a good amount of energy can dissipate from the barrier, showing the durability of the structure.
- For higher values of submergence length, wave reflection is more and wave transmission is less, whereas energy dissipation is initially high and gradually decreases with increasing value of wave number.
- These simulated results demonstrate that lightweight wave barriers provide better wave energy dissipation than bulky submerged structures.

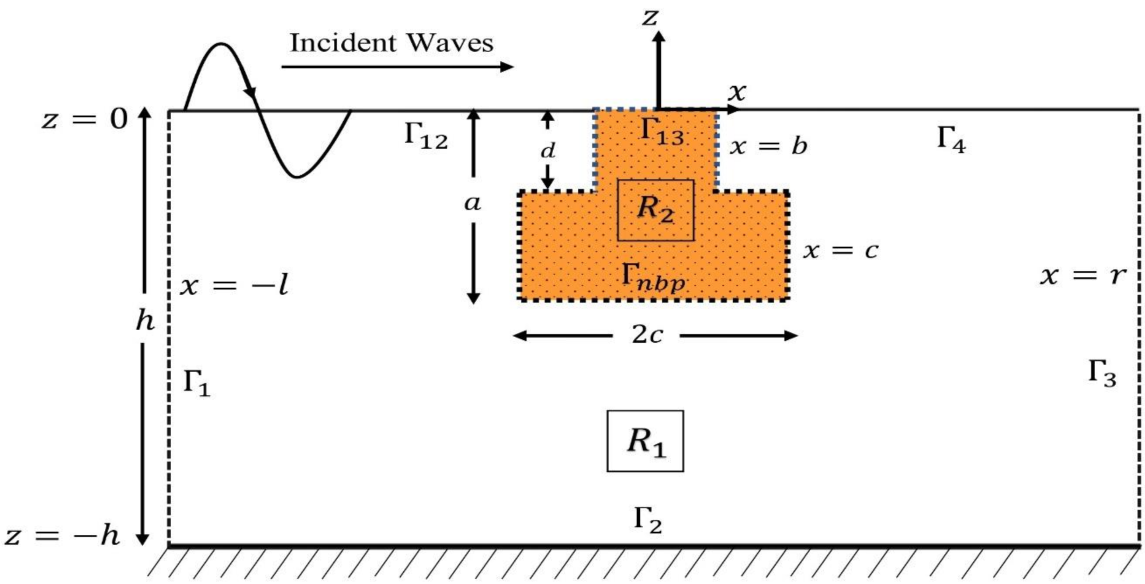

Figure 4Cross-sectional view of the Inverted T-shaped barrier placed over a uniform seabed.

While carrying out this research during these two years, I have also attended a few international conferences, such as the 3rd ICMMCS, 4th ICAPSM, and 10th ICIAM Japan, and presented contributed talks at them. Besides that, I have also participated in an International Workshop IWMCMSE-2023, based on Mathematical and Computational Methods in Science and Engineering, held at IIT Ropar to explore the deep insight of my research objective.

Appendix-2

Summary of the Research Work

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Proposed topic of the research:

Development of Higher Order Boundary Element Method for Mathematical Modeling of Wave Energy Converter Devices.

Summary

In this modern era of industrial-based applications, researchers always try to find an efficient tool or methodology for analyzing real-engineering problems, which can save computational time. Out of various computational numerical methods like the Finite element method, finite volume method, and finite difference methods, the boundary element method (BEM) has emerged as a well-established and promising numerical technique for analyzing numerous industrial applications, especially of engineering structures subjected to external loading. The idea of using BEM for industrial applications is highly useful due to their fascinating discretization technique and reduction in computational meshing. With this efficient numerical method, as an initial step, we have successfully developed a constant BEM for the two-dimensional elliptic-type partial differential equation by reviewing the available literature and examining its mathematical foundation from the potential theory, Green's functions to Fredholm integral equations. Using this BEM technique, we have studied several real engineering problems as follows: We started by studying the water wave interaction with semicircular surface-piercing porous wave barriers installed on a stepped seabed. The study examines the effect of several structural and geometrical configurations on the wave energy dissipation phenomena experienced by the wave barriers. The research findings depict the applicability of these porous structures on the coastal belt to minimize the impact of high-amplitude ocean waves and dissipate a good amount of wave energy to create a tranquil zone in the harbors. Next, with the application of BEM, we investigated the performance of the OWC wave energy converter device placed over an undulated seabed in the presence of ocean currents. The intricate relationship between water waves and ocean currents provided a deep insight into real engineering problems while analyzing the hydrodynamic performance of OWC device. The presence of currents reveals that with a suitable combination of structural configurations and bottom topography, an efficient amount of wave energy can be harnessed by these wave energy converter devices in various wave climates.

Appendix-3

Plan of Work for the Next Year

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➢ Proposed topic of the research

Development of Higher Order Boundary Element Method for Mathematical Modeling of Wave Energy Converter Devices.

➢ Objectives

The main objectives of the proposed research are as follows:

- To develop a higher-order boundary element method to model the hydrodynamics associated with wave energy converter devices.
- To study the performance of OWC wave energy converter devices placed over undulated real seabed in case of random waves.
- To study the convergence of the numerical solutions obtained from the developed higher-order boundary element method.
- To achieve maximum performance of the WEC devices, the efficiency of the device will be analyzed by considering different structural parameters.

➢ Work Plan

In the realm of wave energy concept, it is of utmost importance to consider the impact of ocean currents in the wave propagation scenario. In general, water waves propagate under the influence of currents which are generally driven by several tidal forces of the wind, sun, and geographical phenomena. When currents propagate along with the ocean waves, the transformation in the speed can be predicted, and a huge amount of energy can be transferred due to their long-term steady and continuous flow nature. This continuous, predictable form of kinetic energy will be immensely beneficial for harnessing to provide clean electricity, which is a big challenge for the upcoming sustainable future. In the coming year, the main objective of our research will be studying the kinematics and hydrodynamic performance of OWC devices in the context of random waves and currents. A detailed investigation will be done in the realm of the real marine environment, and the presence of following and opposing currents will be analyzed thoroughly. A detailed study will be carried out for the aforementioned problem by reviewing the literature and to address the same, a numerical solution technique based on the boundary element method will be used. The findings of the research will be beneficial for several coastal engineers in the realm of energy production from the renewable source of energy.