

Site Feasibility Study for Deployment of Offshore Seaweed Aquaculture Prototype System in Open Sea

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Abstract—Utilizing metocean data within a specific region can be pivotal in establishing design criteria for offshore or nearshore infrastructures. This application mitigates the risk of structural failure and prevents overdesign, thereby optimizing the efficiency of the infrastructure. The hindcast approach is the standard method of using metocean data to forecast a coastal region's wave and climatic conditions. This study is part of a project to design a nearshore structure for seaweed cultivation. It focuses on collecting and analyzing metocean data from potential sites in Malaysia to ensure the structure is designed appropriately. Analyzing metocean data is crucial for predicting future environmental conditions. The study investigates the metocean environment to inform the spatial design and monitoring of a seaweed aquaculture farm at the following potential sites: Western Coast near Langsuir Cave, Pulau Langkawi; Eastern Coast near Bachok, Kelantan; Eastern Coast near Setiu Wetland or River; Terengganu, Western Coast near Bidong Island, Terengganu.

Keywords—site selection, seaweed, South China Sea, meta ocean data, prototype

I. INTRODUCTION

There has been a noticeable uptick in companies engaging in Joint Industry Projects (JIP) for specific endeavors in recent years. While this approach offers cost-saving advantages, it also introduces potential risks, including the loss of shared equipment and data, prolonged delays in finalizing the technical scope, and the intricacies of managing multiple contracts. Nonetheless, companies demonstrate a heightened willingness to collaborate on their acquisition when collecting metocean data—a type of information that is not deemed sensitive or confidential. Swail *et al.* [1] described that the hindcast approach uses numerical models and historical meteorological data to simulate surface winds and ocean wave responses. Metocean data is commonly used to design offshore structures for safety and financial considerations. Accurate measurements and databases are crucial for collecting critical data on wind, wave, and storm surges to reflect environmental loads and extreme conditions [2].

The design criteria for specific sites can be established through the statistical process of extremal analysis of hindcast data. Inadequate offshore or nearshore structure design can pose significant safety risks, underscoring the importance of meticulous data collection and analysis. Ensuring that engineers understand comprehensively is vital for effectively strategizing offshore projects. Conversely, excessive utilization of steel in fabrication may arise from over-designing [3]. Thus, the design criteria should be sufficiently conservative to fulfill present requirements while accommodating future structural modifications [4].

The study aims to gather historical metocean data, use MIKE 21/3 HD FM software to model and simulate the current metocean conditions and analyze and calibrate the metocean data for each potential site. A prototype was later deployed on Bidon Island.

Seaweed comprises diverse species adapted to specific habitats with unique environmental conditions. It's essential to assess potential project locations, especially for spatial planning carefully. Due to seaweeds' sensitivity to environmental changes, a comprehensive site evaluation is necessary for successful farm establishment and sustainability.

II. STATE OF THE ART

Recent trends show a significant increase in companies participating in Joint Industry Projects (JIPs) for specific initiatives. Cost-saving benefits drive these collaborative efforts. However, they also come with risks, such as the potential loss of shared equipment and data, delays in defining technical scopes, and the complexity of negotiating multiple contracts [5]. Nonetheless, collecting metocean data, which is typically non-sensitive and non-confidential, encourages collaboration among companies. Enhanced funding for such projects can improve equipment safety and data collection accuracy [6, 7].

Examples of notable JIPs include the Gulf of Mexico Storm Hindcast of Oceanographic Extremes (GUMSHOE), the North European Storm Study (NESS/NEXT), the Southeast Asia Meteorological and Oceanographic Study (SEAMOS), and the West Africa Extremes Study (WAX).

Metocean data is crucial in joint projects, especially for long-term non-strategic technologies. During developing the ISO standard for offshore structure design, significant uncertainty was identified in setting minimum deck elevations. Addressing this issue requires extensive metocean data, including the distribution of crest heights in storm conditions and extrapolation to very low probabilities with return periods of 10,000 years [8, 9].

Hindcasting, a numerical modeling technique, assists in processing and analyzing metocean data by studying the distribution of metocean conditions. This approach is valuable because faulty measuring equipment can create data gaps, which have occurred in oceanographic data from regions such as the northern United States, the Gulf of Mexico, and Prince William Sound. Artificial neural networks have been used to address these gaps by developing buoy networks, although some data were still missing [10].

Tampering with measurement data can interfere with the statistical assessment of offshore structures' oceanographic

and extreme condition design parameters. Despite inevitable data gaps and the time required to repair and reinstall faulty devices, hindcasting remains cost-effective and provides consistent data compared to direct measurements.

The primary application of metocean data is in offshore structures' design and construction standards, impacting operating companies' safety and financial aspects. Accurate measurements and databases for wind, wave, and storm surge data are crucial for assessing environmental load conditions and extreme values [11, 12]. Metocean data helps determine the design criteria for offshore or nearshore infrastructures, preventing structural failures and overdesigning. Statistical extremal analysis of hindcast data provides specific site design criteria [13, 14].

Under-designing offshore or nearshore structures can pose safety risks, making it vital to gather and analyze accurate data for engineers to use in planning projects. Conversely, over-designing can lead to excessive use of steel in fabrication [15]. Therefore, design criteria must be conservative enough to meet current needs while allowing for future modifications.

III. METHOD AND MATERIALS

A. Met Ocean Data Investigation

Metocean data study can also be known as wave climate study. A study on the wave climate data of the Caribbean Sea was carried out by [16], and the methodology of the study included utilizing a Third-Generation (3G) wave model adapted on a nested grid system and a Two-Dimensional (2-D) hydrodynamic model. These models can be used to describe currents that are generated by storms and water level

anomalies. Data validation entailed comparing continuous wave hindcast results with sea state measurements from NOAA data buoys at a specific location and wave height data from TOPEX and ERS satellite altimeters across the entire basin—the verification process centered on analyzing paired data and probability distributions.

Ocean data collection involves measuring instruments such as buoys and wave radars to observe wave heights and directions in a specific region. Anemometers are also installed on offshore platforms to measure wind speed and direction [17]. Wave radars have various applications, including structural monitoring, weather forecasting, sea state assessment for operations, water level observations, and wind farm monitoring. Instruments can malfunction, leading to missing data; however, the fragmented data acquired from the instruments are still used for processing and analysis. Therefore, offshore structures' design and operation projects depend on hindcast modeling.

Hence, this section includes the methodology of met ocean data, which are commonly used by companies for joint projects, as well as the environmental factors that affect the survivability and growth of the native seaweed species in Malaysia. (Fig. 1(a)–(c)).

The study included collecting historical metocean data (tidal elevation, u velocity, v velocity, current speed, current direction, temperature, and salinity) from reliable sources for potential sites. Additionally, metocean data of current conditions for potential sites was gathered using measuring instruments. b. Modeling and simulating the environment based on the data collected of present met ocean conditions using MIKE 21/3 HD FM software. c. Processing, analyzing, and calibrating each potential site's met ocean data [18].

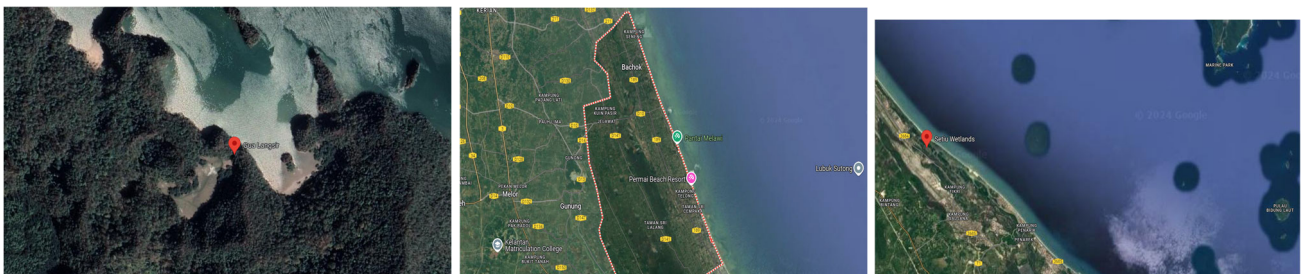


Fig. 1. (a) Google Earth image of coastal regions around Langsur Cave, Pulau Langkawi; (b) Google Earth image of coastal regions near Bachok, Kelantan; (c) Google Earth image of coastal regions near Setiu River/Wetland and Bidong Island, Terengganu.

B. Environmental Factors Affecting Seaweed and Farm Mooring System

1) Temperature

Malaysia generally only experiences wet and dry seasons, and the climate is warm throughout the year. This can affect the sea temperature where the native seaweed dwells. One common native species, "Eucheuma Seaweed," thrives in 25 to 30 °C sea temperatures. The seaweed planted in Pulau Pangkor thrived at a temperature under 35 °C. Meanwhile, another study recorded the temperature range for the native species at two related potential sites, Bidong Island and Setiu in Terengganu, Malaysia. The sampling resulted in the native species of Bidong Island, "Sargassum cristae folium," thriving in the temperature range of 24–34 °C, "Enteromorpha Intestinalis" of Setiu recorded 20 to 33 °C and *Ulva Lactuca* of Setiu resulted in 22–34 °C [19]. Hence, it is generally understood that seaweeds cannot withstand

temperatures above 35 °C.

2) Salinity

Salinity refers to the salt content of seawater. Seaweeds must not be placed at the mouth of the river or anywhere near freshwater as they cannot survive in freshwater. Hence, seaweeds generally thrive in salinity of over 20 ppt (parts per thousand). *Eucheuma* seaweed is listed for more than 28 ppt in salinity [20, 21]. Meanwhile, "Sargassum cristae folium" in Bidong listed 30–33 ppt, "Ulva Lactuca" in Setiu with 19–22 ppt and "Enteromorpha Intestinalis" of Setiu with 8.2 to 25 ppt. Depending on the type of species that will be deployed in this project, it is best to find a location with salinity that is an optimum match with the seaweed.

3) Depth and sunlight/light intensity

The depth of where the seaweeds will be placed is crucial in ensuring optimum seaweed growth as it correlates with the sunlight they receive during the day. Based on this, the light

intensity required by the seaweed is more than $50 \mu\text{mol photon m}^{-2}\text{s}^{-1}$. Therefore, when deploying the farming structure, it is crucial to determine that the depth between the seaweed and the water's surface should be at least 2 m to get this amount of sunlight. The seaweeds planted in Pulau Pangkor are measured at an average 1.5 to 2 m range.

4) Ocean current

Water current mainly involves the current speed and direction of the potential study sites over a certain period. It is essential to analyze and recognize the water movement pattern of a particular area before deploying the seaweed farming structure. The current speed may cause excessive drag force to the seaweed and the mooring components. According to..., a current speed of over three m/s will cause a sizeable intolerable drag force. In addition, the direction of the water current is essential to minimize the drag force when the structure is placed so that the current goes through the seaweed farm instead of against it. The overall result from the study can be simplified in the following tables [22].

5) Bathymetric/geographic conditions of sites

The project focuses on the aspect of a deep-sea mooring system in which, despite native species naturally inhabiting reef flats and sandy slopes, the condition of the seabed does not significantly affect the seaweed planted on the farming structure. However, the mooring design of the structure will require determining the type of seabed on any potential sites so that the mooring will be effective and able to withstand being swept away by the current. Tables 1 and 2 show drag forces and current parameters [23].

Table 1. Current speed and drag force for mooring components and seaweed

Current Speed (m/s)	Drag Force
1–1.5	Minimal
2–3	Large
>3	Large (Intolerable)

Table 2. Current direction and drag force for mooring components and seaweed

Current Direction (Degree)	Max Drag Force
0–10	Ultimate limit state
90	Accidental limit state

This section describes the general methodology of the study, which is used to achieve the project's aim and objectives. Metocean data studies typically entail acquiring historical metocean data covering no less than 20 to 30 years from reputable sources. The duration depends on the particular area of interest or potential sites under consideration. Besides, met ocean data collection of the present conditions of the possible sites is also carried out via measuring instruments that are available and reliable. After collecting the met ocean data, the data will be processed and analyzed via numerical and hindcast modeling. For this study, it is suggested that MIKE 21/3 HD FM software be utilized to analyze, simulate, and calibrate the models.

C. Met Ocean Data Collection

To assess the met ocean environment of the potential sites,

the historical met ocean data from trusted sources and met ocean data of current conditions obtained from measuring instruments of the region must be obtained first, as stated in the first objective of this study. Some of the potential sites are considered to be close to one another. For sites that are relatively near each other, collecting data at each site will not be necessary as the hindcast data is spatially homogenous over a large area for a specific region (Shaw and Shell Global Solutions, n.d.). Thus, only one met ocean data set will be taken for sites relatively close to each other. The following is the number of data collection that will represent several potential sites:

- 1) Western Coast near Langsuir Cave, Pulau Langkawi
- 2) Eastern Coast near Bachok, Kelantan
- 3) Eastern Coast near Setiu Wetland or River, Terengganu, and Western Coast near Bidong Island, Terengganu.

The parameters for the data used in the hindcast modeling will include wind speed and direction, wave height, and current speed and direction. Moreover, there are several sources where met ocean data of specific regions can be obtained. Namely, You can obtain meteorological and oceanographic data for specific areas from sources like the University Corporation for Atmospheric Research (UCAR) and the National Center for Atmospheric Research (NCAR), which provide several products or programs that have online databases on ocean parameters such as the Climate Forecast System Reanalysis (CFSR) [24], Surface Flux and Meteorological Dataset: National Oceanography Centre (NOC) V2.0 [25], Global Sea Level from TOPEX and Jason Altimetry [26].

D. Numerical Hindcast Model

For each parameter specified in this study, the wind, wave, and current, the result produced via numerical hindcast modeling should include clear and well-presented simulations of the conditions over a selected period. Furthermore, the results of the numerical modeling will then be verified based on the guidelines provided by the Department of Irrigation and Drainage Malaysia (DID). The following excerpt is the guideline by DID on the verification of numerical models;

Model verification involves comparing predicted water levels and current velocities with measured values. Verification stations will be located separately from calibration stations near points of interest. The number of calibration points should match the model or project size. The following information must be submitted for evaluation:

- a) A diagram depicting the water level disparity facilitates a comparative analysis between projected and observed values.
- b) A diagram delineating the variance in velocity, offering a visual contrast between projected and observed speed and direction.
- c) Mean disparities in water levels, current speed, and direction.

The average discrepancies in speed and direction should be at most 30% and 45 degrees, respectively. Moreover, the average variance in water level should be at most 10%. It is imperative that the general trends of speed and direction exhibit similarity. Discrepancies between projected and recorded values will be treated as absolute values and averaged over the comparison period. The interval between consecutive values should be under 60 minutes (2001).

After that, the models must be calibrated should the average differences exceed the range stated in the excerpt. This process entails comparing projected water levels and current velocities during spring and neap tides with the measured values and adjusting model parameters as necessary [28]. This is to ensure that the two data sets match each other closely.

The following list is the information that should be in the model calibrations which DID require:

- i) The adjusted values of all model parameters (e.g., roughness coefficient, eddy viscosity, etc.).
- ii) A water level difference diagram (depicting the

comparison between predicted and measured water levels).

- iii) A velocity difference diagram (demonstrating the comparison of predicted and measured speed and direction).

IV. RESULTS

A. Statistics of Simulated Data and Model Calibration

Fig. 2 displays statistics of simulated data for tidal elevation, including a comparison of predicted versus simulated values. Figs. 3 and 4 show the maximum simulated tidal elevation and maximum simulated current speed. Fig. 5 illustrates the mean simulated current direction.

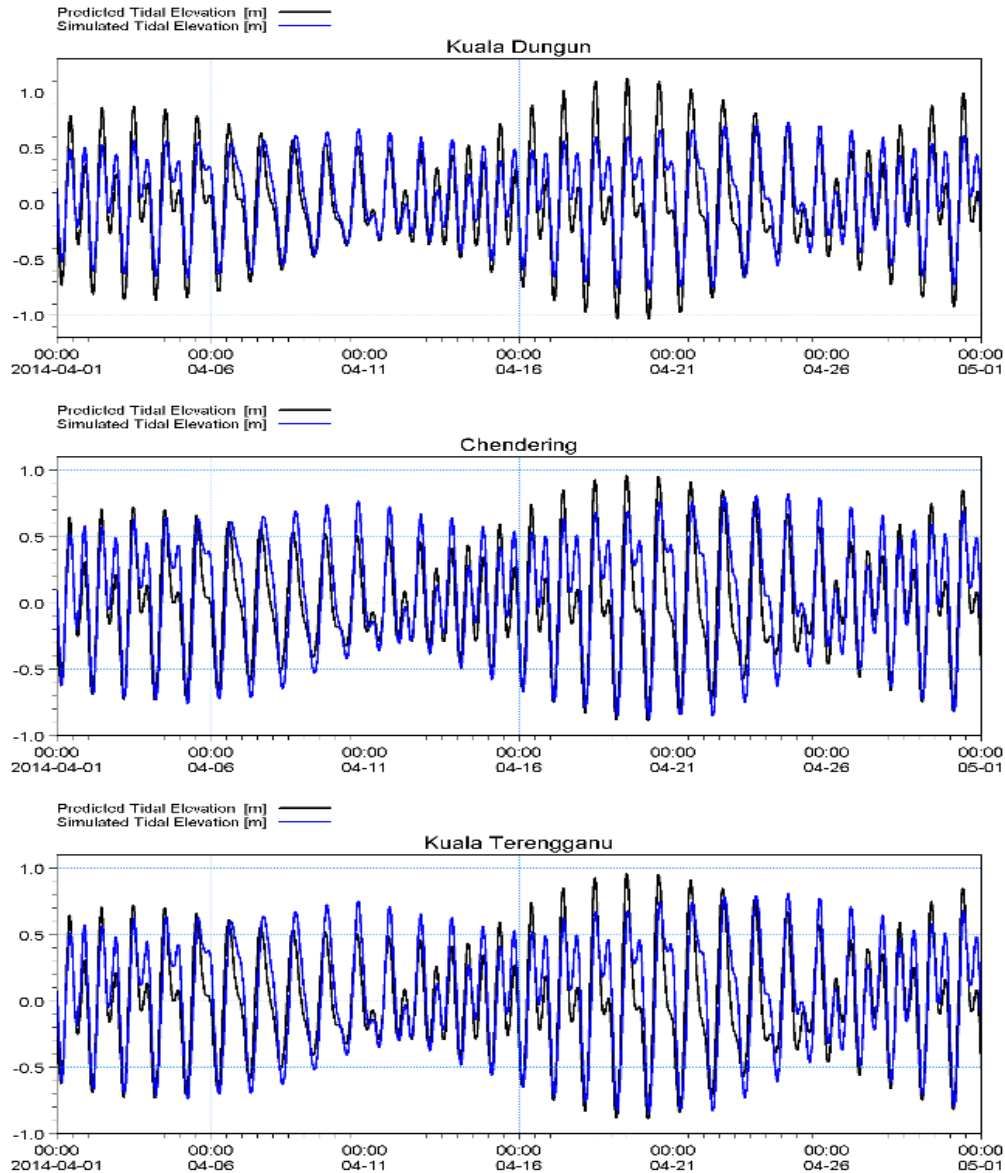


Fig. 2. Statistics of simulated data for tidal elevation.

B. Physical Characteristics on the East Coast of Peninsular Malaysia

This is an overview of the physical characteristics of the sea in the northern part of the east coast of Peninsular Malaysia. This observation data can represent the coastal area of Terengganu and Kelantan in general terms. The time series data of temperature profile, current (in spectral density diagram), and wave characteristics are provided. Most of

these datasets are extracted from a long-term observation data collection by INOS from 2012 to 2015. Fig. 6 shows the time-series of temperature profile from buoy observation during May to August 2014. The surface temperature during these months remained constant between 29–30 °C. A common feature was observed where the temperature decreases with increasing depth. However, it is important to note that there was a sudden drop in the temperature record during June 2014.

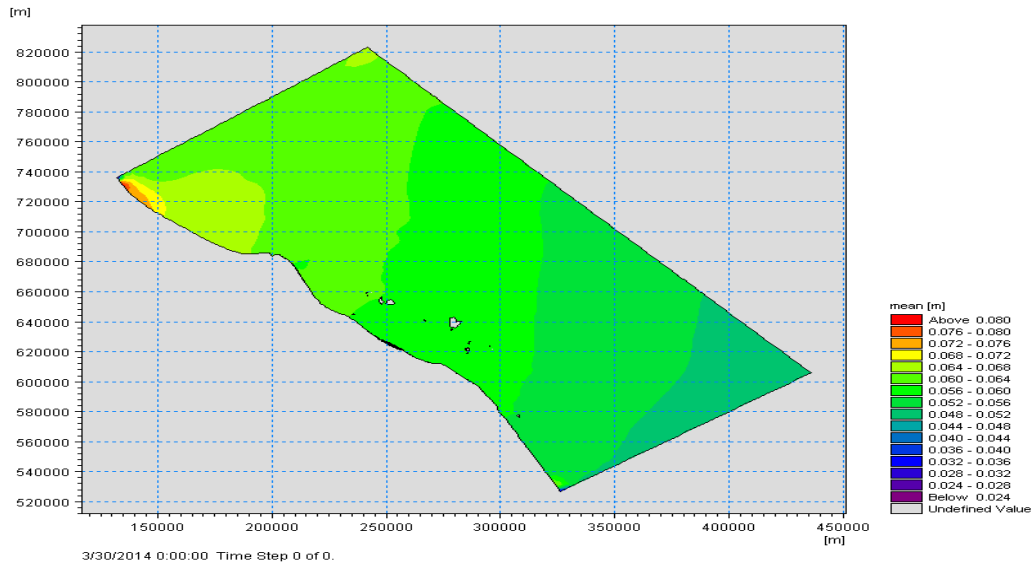


Fig. 3. Maximum simulated tidal elevation.

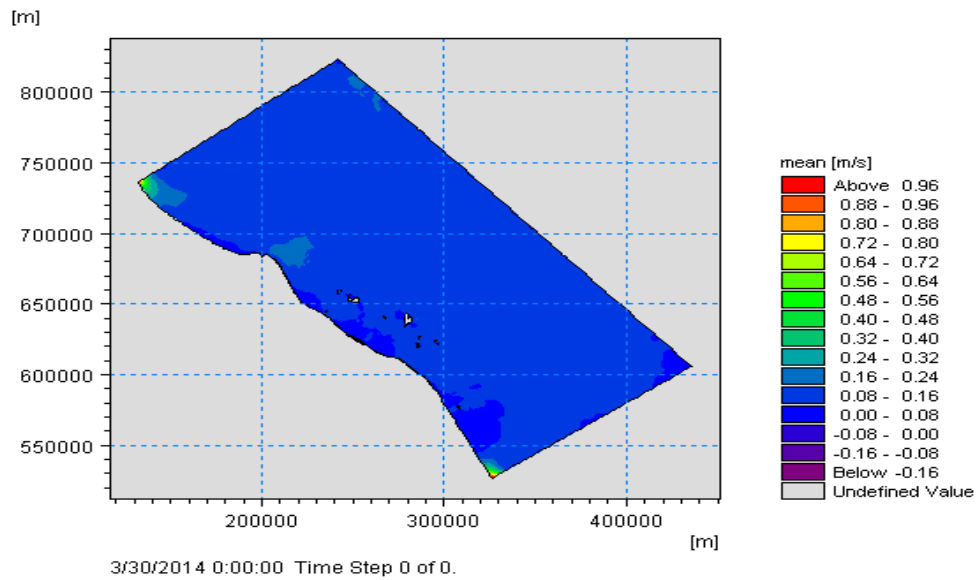


Fig. 4. Maximum simulated current speed.

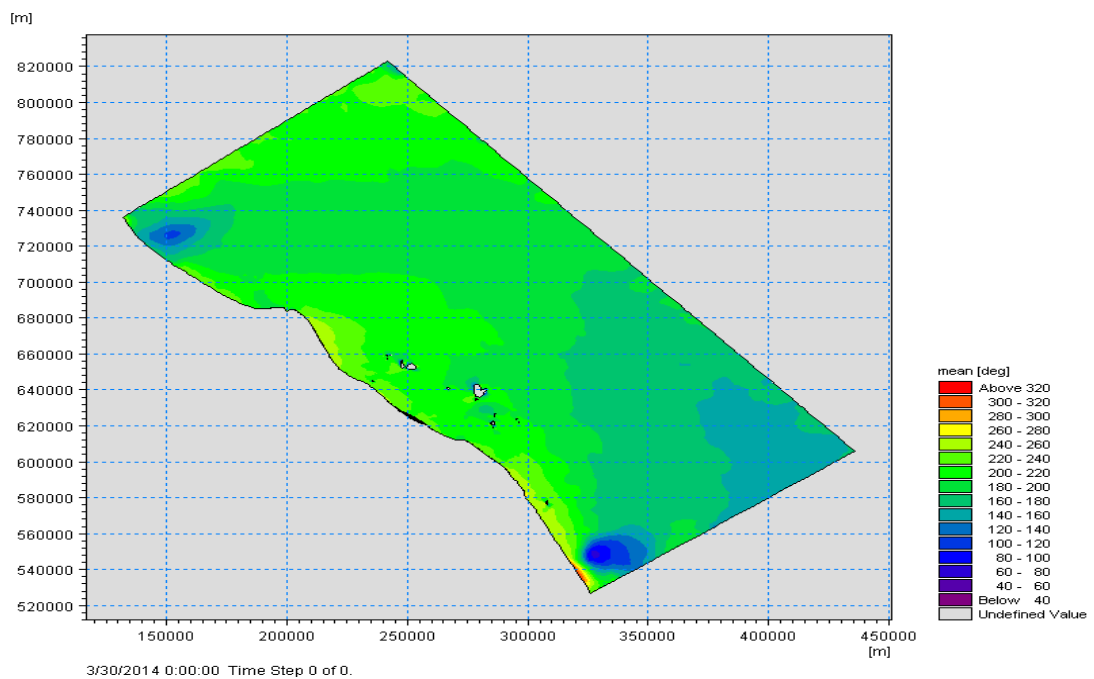


Fig. 5. Mean simulated current direction.

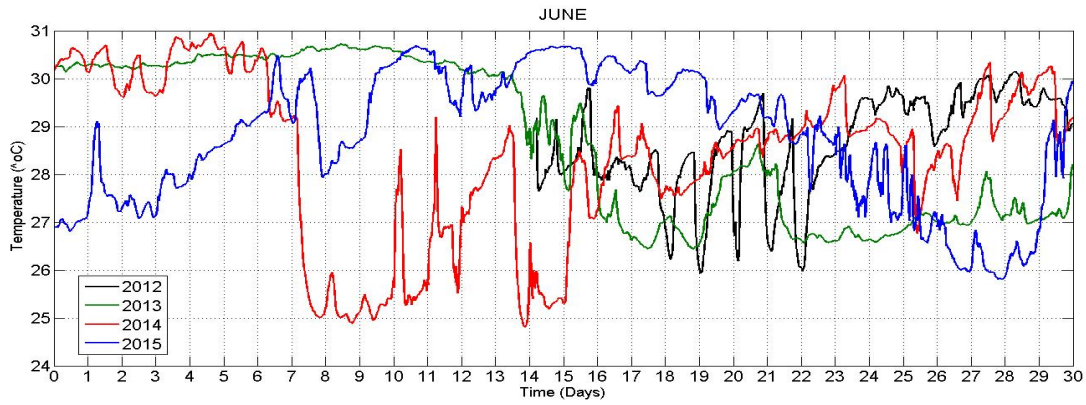


Fig. 6. Temperature time series from buoy observation from 2012–2015 during June.

The compilation of previous temperature records from June 2012 to 2015 also demonstrated the same result (Fig. 7),

where there was a drop in temperature. The drop in temperature was slightly apparent and up to 4 °C.

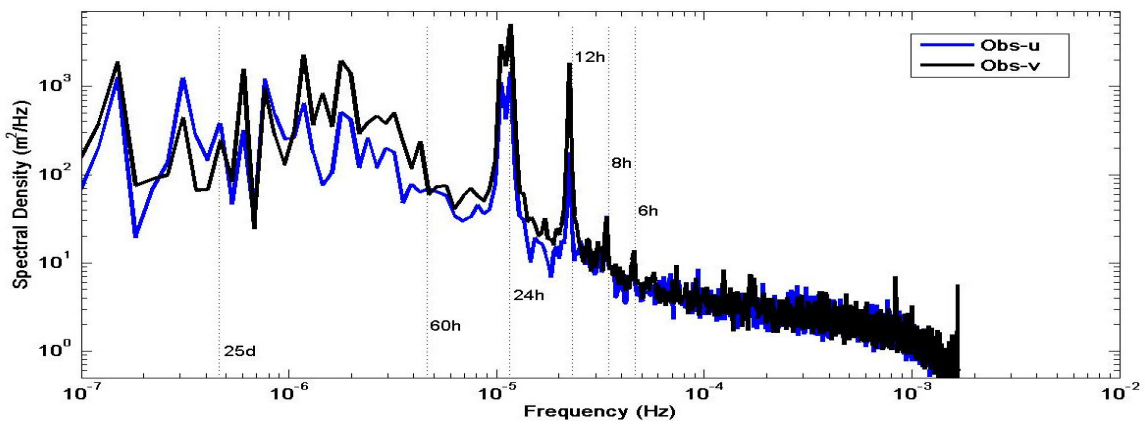


Fig. 7. Spectral density of the current components.

To determine the dominance of the tidal cycle, spectral density was plotted (Fig. 8). The figure clearly shows that the area was characterized by mixed tides with the dominant diurnal tides.

Fig. 5 shows the time series of significant wave height from the 28th of November 2013 to the 26th of February 2014. Based on the figure, the three highest significant wave height values were detected each month on the 2nd of December 2013, the 10th of January 2014, and the 25th of

February 2014, with 2.58 m, 2.44 m, and 2.88 m, respectively. The lowest values are 0.47 m, 0.67 m, and 0.27 m on 17th December 2013, 4th January 2014, and 11th February 2014, respectively. With wind blow from the South China Sea, the significant wave height value collected from sampling is much higher than the estimated tide value. This indicates that tides and winds during the northeast monsoon season produce rage waves, contributing to severe shoreline erosion.

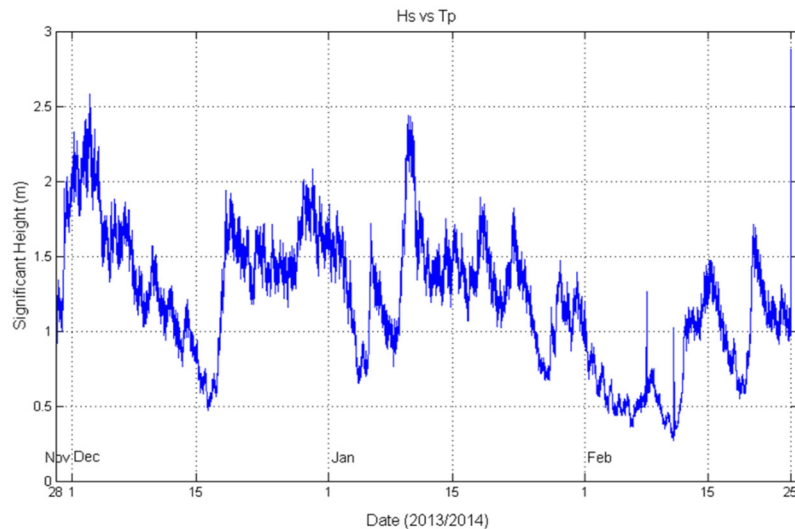


Fig. 8. Time series of significant wave height.

V. 10×10 PROTOTYPE DEPLOYMENT

A 10×10 m new prototype was deployed after the Northeast Monsoon. The length and depth of each mooring

system were approximately 20 m in length and 10 m in depth during high tide, except for one mooring point near the crane machine, which was less than 20 m in length. (Fig. 9). Table 3 shows deployment parameters, and Table 4 shows the buoy's position.



Fig. 9. Prototype trial at Bidun Island.

Table 3. Deployment activities, data, and equipment

Activity	Data	Equipment
10x10 Prototype deployment	Coordinates	Garmen GPS
Fouling organism	Sample identification (done)	Microscope
Seaweed planting	Fresh weight measurement and planting baskets cleaning (done)	Electronic balance
Environmental condition	Hydrological parameters (NA)	YSI multi-probes
Nutrient analysis (done) Water sample bottle	Image recording (done)	Digital camera

Table 4. The coordinates for buoys (A, B, C, D) were recorded as follows

Buoy A	Buoy B	Buoy C	Buoy D
N 05 37.254	N 05 37.256	N 05 37.261	N 05 37.256
E 103 03.383	E 103 03.388	E 103 03.388	E 103 03.392

A. Seaweed Planting

Species of *Ulva* and 2 *Gracilaria* were measured for their fresh weight (as initial weight) and kept in planting baskets with dimensions (26 (L)×19 (W)×9 (H) cm) and volume (4.45 L) and covered with fishing net (1.5 cm mesh size). Stocking density for *Ulva* is 2.5 g/L and 5.0 g/L for both *Gracilaria* species, and triplicates of samples were studied. Three baskets were tied on the same line and parallel with another two lines, with three baskets each. After two weeks, growth measurements were conducted biweekly in situ.

After 14 days, baskets for *Ulva* were empty due to all samples lost in the planting units. *Gracilaria* sp.1 remained in triplicates and growth measurements for up to 28 days. For *Gracilaria* sp.2, all triplicates' samples were reweighed after 14 days, and new stocking densities of 7.5 g/L in the original triplicates and 2.5 g/L were replaced in each empty basket. However, after 28 days, one of the 2.5 g/L *Gracilaria* sp.2 replicates was lost due to the improper tie.

The growth rate for *Gracilaria* sp.1 on day 28 decreased from 3.84 %·day⁻¹ to 2.15 %·day⁻¹. *Gracilaria* sp.2 for two stocking densities, 7.5 g/L, and 2.5 g/L, showed different

growth rates, which were 3.31 %·day⁻¹ and 3.42 %·day⁻¹, respectively, on day 14. *Gracilaria* spp. were archived doubling time in 15–17 days, showing that the environment is still suitable for growth. New branching tips were observed to be more prominent on seaweed thalli, and branches became thicker. However, the growth rates for both *Gracilaria* spp. decreased from day 14 to day 28 with possible reasons: nutrients, light and space competition between seaweed and fouling organisms; seaweed stock used for cultivation was kept in the hatchery for two months and getting older before cultivation started; tropical temperature making growth synergy slow due to high metabolism rate.

All *Gracilaria* samples were covered with epiphytic organisms like micro- and macro-algae and invertebrates. Besides, the net covering and planting basket were also attached with tiny brownish fouling invertebrates or microalgae and became abundant on day 28 for all baskets. Since the fouling organisms were too abundant and firmly attached to the net covering, after fresh weight measurement, all baskets were without cleaning planting baskets and tied back to the prototype for following growth observation.

List of fouling and epiphytic organisms: Invertebrates: Sea hare, copepod, roundworm, shrimp (Fig. 10). Vertebrates: fish (not considered as fouling) (Fig. 11). Microalgae: diatom mainly pennate diatom. Macroalgae: unidentified cyanobacteria; Bryopsis, Chaetomorpha, Cladophoropsis (green seaweed); Acanthophora, Herposiphonia, Laurencia, Polysiphonia, Tolypocladia (red seaweed) (Fig. 10).



Fig. 10. Some invertebrates and vertebrates.



Fig. 11. Fouling and epiphytic macro-algae, water was brought back to conduct physicochemical parameters in the lab, and analyses of nutrients and salinity were checked. Salinity was 33ppt; NH_4^+ 0.1346 mg/L; NO_2^- 0.0077 mg/L; NO_3^- 0.9827 mg/L; PO_4^{3-} 0.0034 mg/L.

B. Discussion

The study presented a comprehensive approach to the feasibility analysis of deploying an offshore seaweed aquaculture system in Malaysia, emphasizing the importance of metocean data in ensuring structural safety and operational efficiency. This discussion synthesizes the findings and implications of the research, highlighting key aspects such as data collection, environmental factors, and the practical challenges faced during prototype deployment.

Metocean data, encompassing parameters such as tidal elevation, current speed and direction, temperature, and salinity, is critical for designing offshore structures. Accurate data prevents under-designing, which could lead to structural failure, and over-designing, which results in unnecessary costs. The study utilized historical and real-time data from various coastal sites, processed through numerical modeling software (MIKE 21/3 HD FM), to simulate the environmental conditions accurately. This approach aligns with established methodologies in the field, providing a robust framework for assessing the feasibility of offshore

projects.

The environmental conditions of the selected sites were carefully analyzed to ensure they met the requirements for seaweed cultivation. Temperature, salinity, light intensity, water movement, and bathymetric conditions were all considered. For instance, seaweed species such as *Eucheuma* and *Gracilaria* thrived within specific temperature and salinity ranges. The study noted that temperatures above 35 °C and salinities below 20 ppt could be detrimental to seaweed growth, aligning with findings from previous research.

The depth and sunlight availability were also critical factors. Seaweeds require a minimum light intensity of 50 $\mu\text{mol photon m}^{-2}\text{s}^{-1}$, necessitating careful placement of farming structures to ensure adequate light penetration. Another significant factor was water movement, characterized by current speed and direction. Excessive current speeds can cause intolerable drag forces on the seaweed and mooring components, highlighting the importance of selecting sites with optimal current conditions.

One of the practical challenges encountered was deploying the prototype at Bidong Island. The study reported issues such as the loss of seaweed samples and the presence of fouling organisms, which impacted the growth rates of the seaweed. For example, *Ulva* samples were lost within 14 days, and *Gracilaria* species showed decreased growth rates over 28 days. These challenges underline the need for continuous monitoring and adaptive management practices to ensure the success of aquaculture systems.

The presence of fouling organisms, including microalgae and invertebrates, posed a significant challenge. These organisms competed with seaweed for nutrients and light, affecting overall growth rates. The study's detailed documentation of these organisms provides valuable insights into potential ecological interactions that must be managed in future deployments.

The findings from this study have several implications for future research and practical deployment of offshore seaweed aquaculture systems:

- 1) Data Collection and Analysis: Continued improvement in the accuracy and reliability of metocean data collection is essential. Integrating advanced technologies such as AI for data gap-filling and real-time monitoring can enhance the precision of environmental simulations.
- 2) Environmental Suitability: Selecting sites with optimal environmental conditions is crucial. Detailed pre-deployment studies should ensure that the selected sites meet the specific requirements of the seaweed species intended for cultivation.
- 3) Prototype Design and Testing: Iterative testing and refinement of prototype designs are necessary to address fouling and structural stability challenges. Adaptive designs that can be modified based on real-time feedback will likely improve the success rates of such projects.
- 4) Collaborative Efforts: Encouraging collaboration among industry stakeholders can lead to better resource sharing and cost efficiencies. Joint Industry Projects (JIPs) can significantly advance the offshore aquaculture sector, provided the risks associated with data and equipment sharing are managed effectively.

VI. CONCLUSIONS

The study investigated the met ocean environment for the spatial design and monitoring of a seaweed aquaculture farm at the following potential sites: the Western Coast near Langsuir Cave, Pulau Langkawi; the Eastern Coast near Bachok, Kelantan; the Eastern Coast near Setiu Wetland or River, Terengganu, Western Coast near Bidong Island, Terengganu. The study collected historical met ocean data (wave, wind, and current) of potential sites from reliable sources and met ocean data of present conditions of potential sites via measuring instruments. Then, I modeled and simulated the environment based on the data collected of present met ocean conditions using MIKE 21/3 software and processed, analyzed, and calibrated the met ocean data of each potential site. The prototype revealed information required for scale-up.

This study underscores the importance of a thorough feasibility analysis, driven by accurate metocean data, for successfully deploying offshore seaweed aquaculture systems. The research provides a foundational framework for future endeavors in this emerging field by addressing environmental suitability and practical challenges. The insights gained from the prototype deployment at Bidong Island will inform subsequent projects, contributing to the sustainable growth of the offshore aquaculture industry.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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