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Tidal Resource Assessment and Hydrodynamic Simulation of a SeaGen-type Horizontal Axis Tidal Turbine in Verde Island Passage Philippines

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Abstract- The Philippines is a country in Southeast Asia which has abundant natural renewable energy sources. This study focuses on one aspect of renewable energy, which is tidal energy. The tidal parameters such as tidal heights, and tidal currents, of six representative points within Verde Island Passage, were determined through numerical modelling. A decision matrix was used to determine the peak month for tidal energy harvesting, for the year 2017 and a one-month energy density map was created. The SeaGen model of twin horizontal axis rotors were simulated in an area in Verde Island Passage, and the power production of the tidal turbines for the peak month were estimated. Delft3D 4 Suite was used for the numerical modelling and hydrodynamic simulation.

Keywords- hydrodynamic simulation, numerical modelling, resource assessment, tidal energy, tidal turbine

I. INTRODUCTION

Natural resources are only limited and exhaustible, and fossil fuels, which are the primary energy source around the world, are rapidly depleting. Fossil fuels also produce greenhouse gas (GHG) emissions that cause adverse effect in the environment (e.g. climate change), thus, renewable energy alternatives are strongly being promoted. Developing countries such as the Association of Southeast Asian Nations (ASEAN) can especially benefit from renewable energy because there are abundant renewable energy resources in the region [1].

In the Philippines, as of 2009, it was recorded that about 10% of the population do not have access to modern electricity. In 2011, the total household electrification amounted to about 70.18% of the population [2]. As of the end of the year 2014, 83% of the country have grid connections [3]. Most of the population with no access to modern electricity is on or below the poverty line and located in the rural areas of the country. Hence, rural electrification is one of the main objectives of the local energy development [4].

Renewable energy is seen to be the optimal solution to provide clean and sustainable energy for the underdeveloped and un-electrified rural areas. Some of the challenges that hinders the propagation of renewable energy are high initial cost and complex technology. Renewable energy systems are also required to be maintained and monitored by a skilled and technically capable professional [4]. The Philippines have ambitious plans for renewable energy and it is coupled with a comprehensive renewable energy policy, the Republic Act No. 9513, Renewable Energy Act of 2008. The Philippine government, particularly the local Department of Energy, aims to increase the installed capacity for renewable energy by threefold for the period of 2011 to 2030 [2].

The Philippines, being an archipelagic and tropical country, have huge potential for ocean energy harvesting. The Philippine Department of Energy estimated the ocean energy potential of the country at 170 gigawatts (GW) [5]. Whereas according to a study by [6], 40-60 GW of tidal energy in the Philippines are extractable. Under the National Renewable Energy Program (NREP) targets of the Department of Energy for the time frame between 2011 and 2030, is to have a total installed capacity of 70.5 megawatts (MW) derived from ocean energy as part of the aggressive scheme to triple the renewable energy output of the country by 2030 [7].

As of writing, the Philippines is slated to be the first in South East Asia or the ASEAN to develop an ocean tidal power plant utilizing the Tidal In-Stream Energy Conversion (TISEC) technology. In 2013, the Philippine Department of Energy (DOE) awarded four ocean energy service contracts to H&WB Asia Pacific (Pte Ltd) Corp., a Filipino company, and Sabella SAS, a French firm [8].

This research focuses on the assessment of the tidal energy potential of Verde Island passage, an ocean channel located in Batangas, Philippines, which is among the potential areas for tidal energy harvesting in the country [9]. Horizontal axis tidal turbine (HATT) rotors were simulated in a selected area in Verde Island passage. The technical specifications of the turbine rotors were derived from the SeaGen model, the actual structure is shown in figure 1.

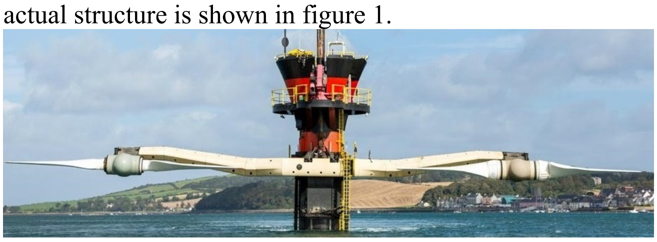


Figure 1: SeaGen tidal turbine [10].

II. RESEARCH ELABORATION

For this research, the methodological or conceptual framework of the study is shown in figure 1.

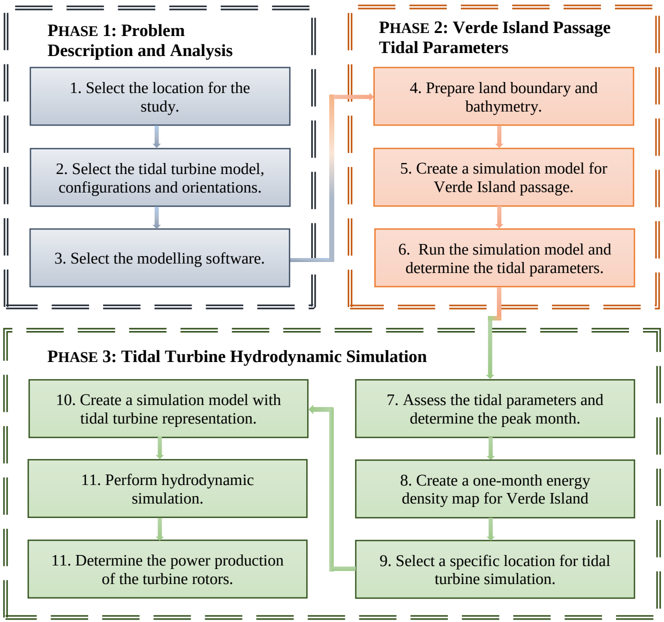


Figure 2: Methodological framework

III. RESEARCH ELABORATION (continued)

A. Phase 1: Problem description and analysis

The study site selected for this study is the ocean channel known as Verde Island passage, located near the province of Batangas, in the Philippines. Based on a previous study [11], Verde Island passage was estimated to have favorable tidal energy potential, hence Verde Island passage was chosen as the site for this study. The map of the Verde Island passage and the map of the Philippines highlighting the Verde Island passage, are shown in figure 3 and figure 4, respectively.

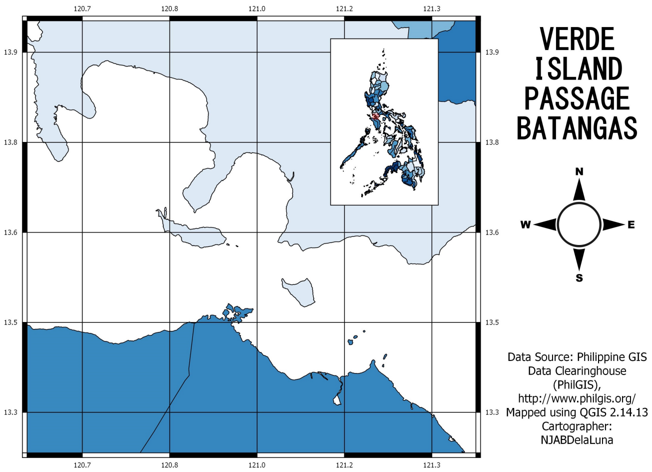


Figure 3: Verde Island passage.

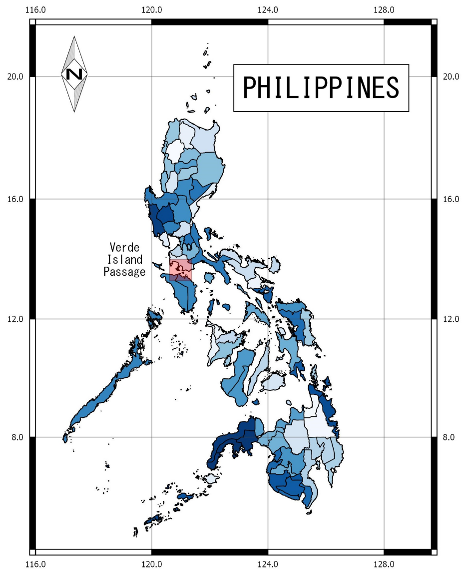


Figure 4: Map of the Philippines.

The SeaGen horizontal axis tidal turbine (HATT) was chosen as the tidal turbine model of this study. The technical specifications needed for the study were derived from the SeaGen model. SeaGen has been the only certified tidal turbine power station in the world, which was continuously operational between the years 2008 and 2016, in Strangford Lough, Northern Ireland [12].

The ocean modelling software used by the researcher is the Delft3D 4 Suite. Delft3D was utilized alongside Delft Dashboard. QGIS and MATLAB were also utilized for other data processing.

B. Phase 2: Verde Island passage tidal parameters

The researcher used nautical chart and bathymetric data from National Mapping and Resource Information Authority (NAMRIA) for numerical modelling to determine the tidal parameters in Verde Island Passage. Bathymetric data from General Bathymetric Chart of the Oceans (GEBCO) was also utilized. Tidal signals from the International Hydrographic Organization (IHO) was also used for verification of the simulation results.

Six (6) observation points were selected, in which tidal heights, and tidal currents (depth-averaged current velocities) were determined for the possible application of tidal turbine rotors. The six observation points are located in (1) Batangas Bay, (2) Anilao, Balayan Bay, (3) Calapan Port, Oriental Mindoro, (4) Lobo, Batangas, (5) Tingloy, Batangas and (6) Verde Island. Batangas Bay and Calapan Port are primary tide stations, while Anilao is a substation. The observations points in Lobo, Tingloy, and Verde Island were selected because they have tidal energy potential based on a preliminary simulation. The processed bathymetric data reflecting the 6 observation points are shown in figure 5, while the simulation or computational model for the tidal energy resource assessment is shown in figure 6.

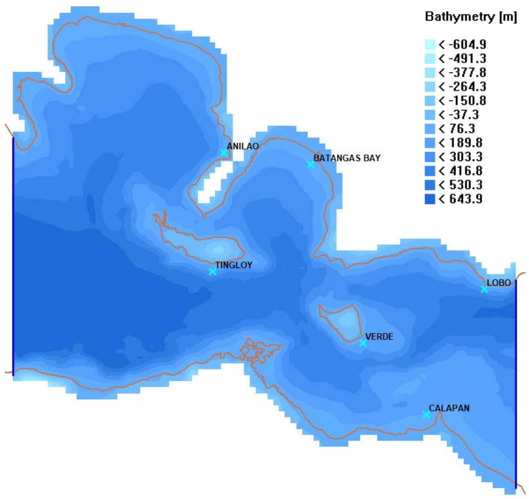


Figure 5: Bathymetric data of Verde Island passage.

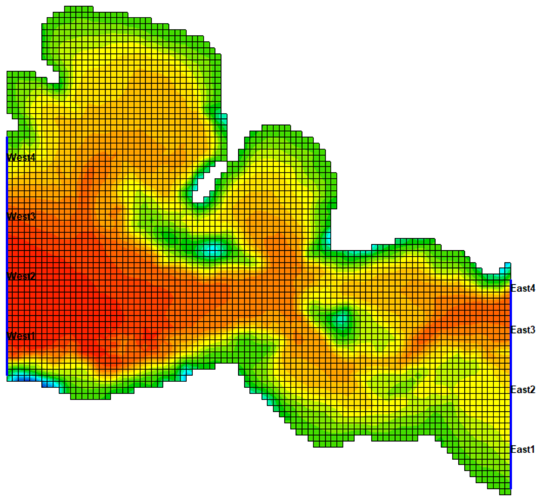


Figure 6: Simulation model used to determine the tidal paramters.

In figure 6, the grid is rectilinear with a resolution of 800 meters. The boundary conditions were derived from TPXO 7.2, a global tide model developed by Erofeeva and Egbert of Oregon State University [13]. Thirteen (13) astronomical tidal constituents with their respective amplitude and phase, were used for the boundary conditions, namely, M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_F, M_M, M_4, MS_4, and MN_4.

The mathematical representation of tide, (applicable to both tidal heights and tidal currents), is shown in equation 1.

$$H(t) = A_0 + \sum_{i=1}^{k} A_i F_i \cos[\omega_i t + (V_0 + u)_i - G_i] \quad (1)$$

Where $H(t)$ is the height at time t, A_0 is the mean water level over a certain period, k is the number of relevant constituents, i is the index of a constituent, A_i is the local tide amplitude of a constituent, F_i is the nodal amplitude factor, ω_i is the angular velocity/frequency, $(V_0+u)_i$ is the astronomical argument, and G_i is the improved kappa number (local phase lag). Tidal heights and currents have the same values for frequency (ω) and most tidal constituents, but they have different values for A_0, A_i, and G_i [14].

C. Phase 3: Tidal turbine hydrodynamic simulation

The peak month of the year 2017 was determined using a decision matrix of the monthly-averaged tidal currents. An energy density map was created for the peak month. The map-wide averaged tidal currents were transformed into energy density using equations 2 and 3.

$$P = \frac{1}{2}\rho\eta A U_0^{\,3} \quad (2)$$

$$E_d = pt \quad (3)$$

In equations 2 and 3, P is power, ρ is the density of sea water, η is the product of turbine efficiency and power equipment efficiency, A is the swept area, and U_0 is the depth-average flow rate or velocity (undisturbed velocity). In equation 3.3, E_d is the energy density, p is the power density, which is the available power per unit of cross-sectional effective area, and t is time.

For the hydrodynamic simulation of the tidal turbine, the turbine rotors were simplified as a porous disc plates in Delft3D because there is no dedicated tidal turbine function in the program. A porous plate file (.ppl) was created and was included in the model. The porous plate file indicated the direction of the porous plates normal to the flow, the start and end nodes of the grid where the porous plates were simulated, the layers that the porous plates occupied, and lastly, the quadratic friction coefficient or the energy loss coefficient. The direction, nodes, and occupied layers were determined within the Delft3D program, whereas the energy loss coefficient was computed using equation 4 [14].

$$c_{loss} = \frac{c_T A}{2n\Delta y \Delta z} \quad (2)$$

In equation 4, c_{loss} is the energy loss coefficient, c_T is the thrust coefficient, A is the swept area, n is the number of layers, Δy is the distance between the grid points along the u-axis, and Δz is the height of a vertical layer.

The rotor diameter used in this study is based on the rotor diameter of the actual SeaGen tidal turbine, which is 16 meters [15]. The minimum and maximum ocean depth at the tidal turbine location was measured to be 65.68 meters and 70.33 meters respectively, thus the average ocean depth is 68.005 meters. The number of layers for this simulation model is set to be eight layers, thus dividing 68.005 meters by 8, yielded a Δz with a value of 8.5 meters. Of these layers, two layers were occupied by the tidal turbine rotors.

The momentum extraction of energy by horizontal axis tidal turbine (HATT) is modelled after the actuator disc theory. There are, however, some differences when modelling HATT with porous disc plate instead of actual HATT, the differences are exclusive on the near wakes. The far wakes of an actual HATT structure and HATT represented as a porous disc will be similar as long as they have the same rotor diameter and thrust force. HATT modelling in Delft3D software is more concerned with the significant effects of the HATT in the hydrodynamics of the selected site, thus, near wake is not significant and the simplified modelling of HATT using porous disc is justified [16].

The turbine rotors were simulated on an area in Verde Island passage that passes the criteria: (1) the tidal turbine must be simulated within 5 kilometers from a land area, which can serve as the support terminal, (2) the ocean depth for the tidal turbine must be in between 10 to 100 meters, and (3) with the tidal resource assessment previously conducted as the basis, the location of should have a good flow rate velocity [17].

The model for the hydrodynamic simulation of the tidal turbine rotors is shown in figure 7. The location of the tidal turbine is directly northeast of Verde island and was chosen based on the previously mentioned criteria. The outer grid resolution is 800 meters, while the refined grid which the tidal turbine rotors were simulated has a grid resolution of 16 meters. A closer look at the grid cells which the turbine rotors occupy is shown in figure 8. Figure 8 shows that the rotors were simulated along the U-direction (horizontal axis) and the location is at the left most part of the grid cells. The computational model was simulated with a period of one month, after which, the power production of the turbine rotors was predicted, using the simulation results. Equation 2 was used to transform the data into theoretical power production.

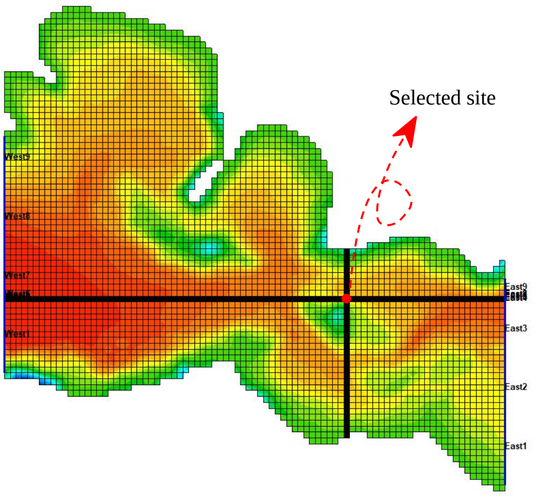


Figure 7: Simulation model for hydrodynamic modelling.

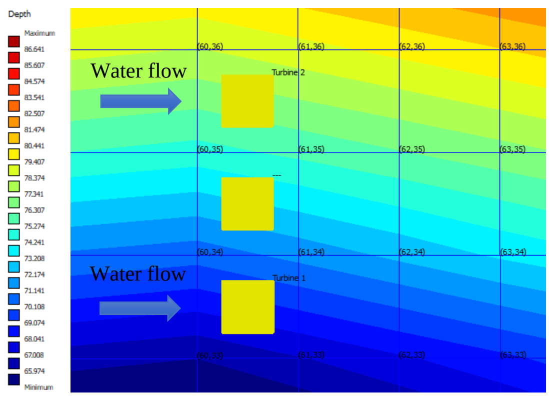


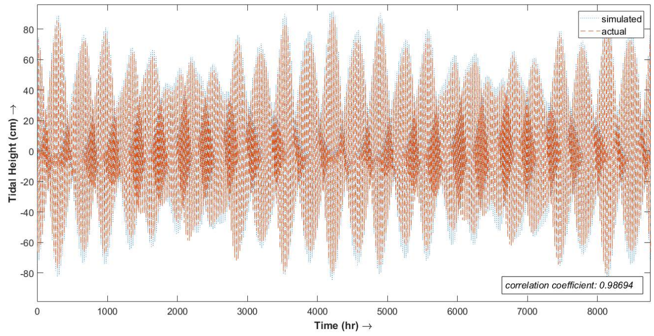
Figure 8: Tidal turbine location; magnified.

IV. RESULTS AND FINDINGS

A. Verde Island passage tidal parameters

The tidal parameters such as the tidal heights and tidal currents of the six observation points, for the full year of 2017, were determined using Delft3D.

To verify the simulation results, a sample comparison was conducted between the simulated and actual (from IHO) full-year tidal height time series, as shown in figure 9. In figure 9, a strong correlation coefficient of 0.98694 is established, which implies that the simulation results for the tidal heights are very similar to the actual data of the IHO.



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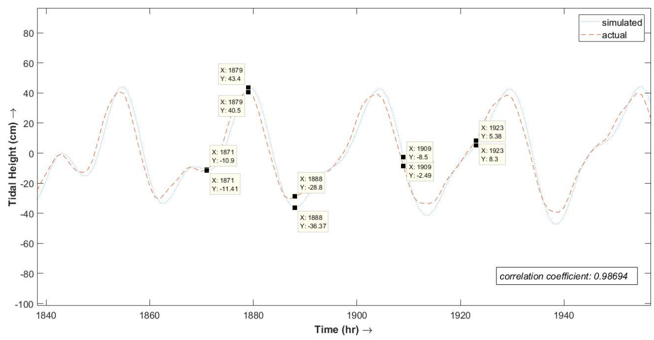
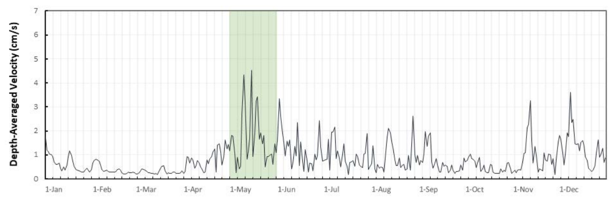


(b)

Figure 9: Actual and simulated tidal heights in Anilao, Balayan Bay (a) Full 1-year data (b) magnified.

The tidal currents (depth-averaged velocities), were estimated with an interval of 60 minutes for the duration of one year (2017). To simplify the data, the tidal currents of the six observation points were averaged per day, as seen in figure 10. In figure 10, the green shaded region is the month with the maximum averaged tidal current velocities.



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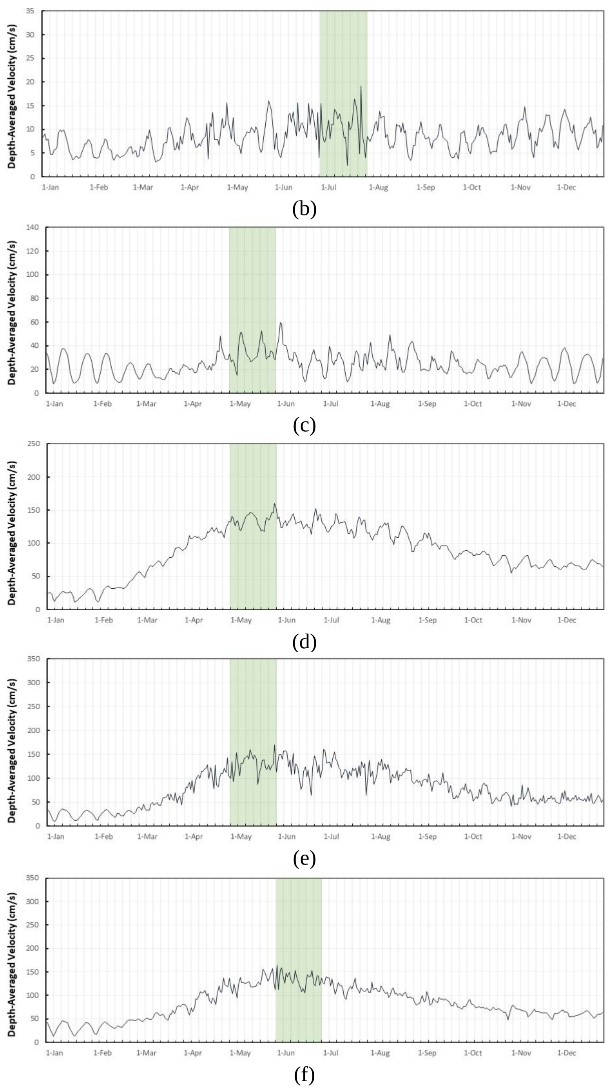


Figure 10: Tidal currents in (a) Anilao, (b) Batangas Bay, (c) Calapan Port, (d) Lobo, (e) Tingloy, & (f) Verde Island.

The tidal current velocities were averaged per month and the resulting data of the six observation points were used to create a decision matrix, as seen on table 1, where the peak month was determined to be May.

Table 1: Monthly-averaged tidal current velocities of the six observation points.

	Averaged current velocity (cm/s)							
Month	**A**	**B**	**C**	**D**	**E**	**F**	**Ave.**	**Rank**
Jan.	0.65	6.58	23.64	22.83	24.21	32.02	18.32	12th
Feb.	0.39	5.31	19.28	32.19	25.14	35.92	19.71	11th
Mar.	0.29	6.31	16.93	71.26	49.27	57.47	33.59	10th
Apr.	0.81	8.92	25.44	112.71	102.39	95.59	57.64	5th
May	1.62	9.58	33.84	135.57	130.2	127.26	73.01	1st
June	1.22	9.89	30.87	132.38	122.14	134.83	71.89	2nd
July	0.93	10.58	25	125.84	122.63	117.46	67.07	3rd
Aug.	0.89	8.72	30.53	112.46	110.1	104.39	61.18	4th
Sept.	0.69	7.63	23.61	95.55	84.68	86.42	49.76	6th
Oct.	0.51	8.01	20.12	80.13	66.55	72.6	41.32	7th
Nov.	0.9	9.55	21.79	68.42	56.93	64.43	37	8th
Dec.	1.27	9.63	23.55	66.75	56.21	60.6	36.34	9th

*A – Anilao, B – Batangas Bay, C – Calapan Port, D – Lobo, E – Tingloy, F – Verde Island

B. Tidal turbine hydrodynamic simulation

The energy density map of Verde Island passage was created for the peak month (May) and is shown in figure 10. Looking at figure 11, the regions within the dash polygons are areas that are outside the 5-kilometer limit, hence areas that are not considered for tidal turbine application. The energy density map shows the tidal energy potential of Verde Island passage for the month of May. The unit of measurement of the energy density map is kilowatt-hour per square meter.

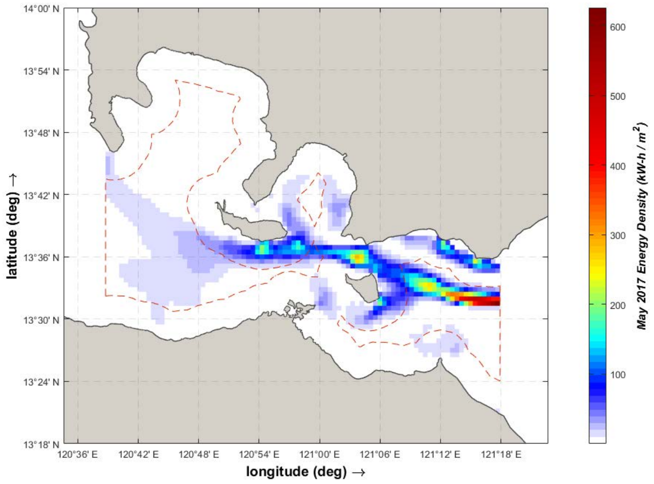


Figure 11: Verde Island passage May 2017 energy density map.

After choosing the suitable study site of the tidal turbine, a porous plate file was created. The file indicates the necessary parameters for the simulation of turbine rotors in Delft3D. The metadata of the porous plate file is shown in table 2.

Table 2: Porous plate file specification

Direction normal to the flow	Begin index (m)	Begin index (n)	End index (m)	End index (n)	First layer occupied	Last layer occupied	Energy loss coefficient
U	60	33	60	34	1	2	0.208
U	60	35	60	36	1	2	0.185

Upon the successful run of the simulation model, the tidal current velocities of the turbine rotors were determined. The instantaneous and daily-averaged tidal current velocities of the turbine rotors are shown in figures 12 and 13.

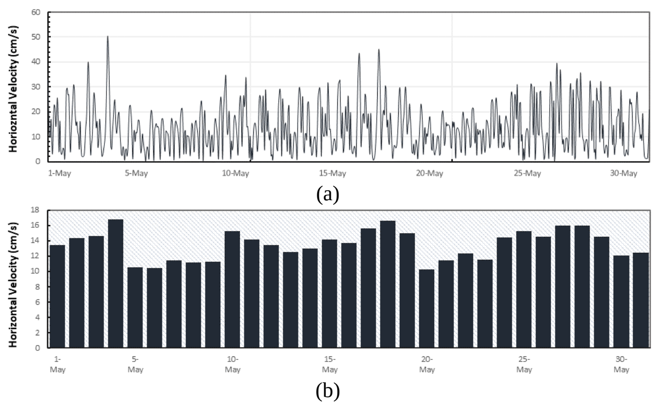
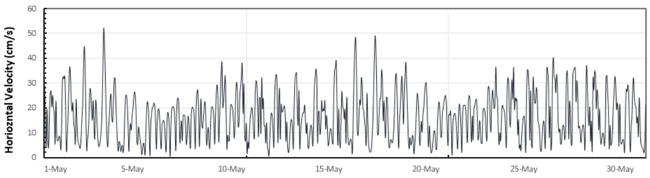


Figure 12: Tidal current velocities of turbine rotor 1: (a) instantaneous; (b) daily-averaged.



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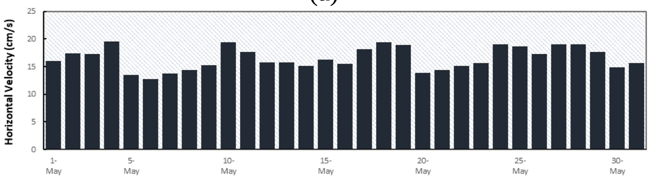
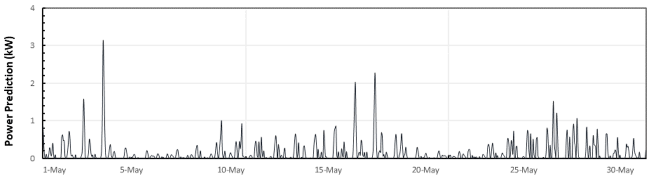


(b)

Figure 13: Tidal current velocities of turbine rotor 2: (a) instantaneous; (b) daily-averaged.

The instantaneous (60-minute interval) and daily-averaged power prediction for the turbine rotors are shown in figures 14 and 15.

For turbine rotor 1, the maximum instantaneous power is 3.114 kW, while the maximum daily-averaged power is 0.376 kW, and the monthly-averaged power production, seen as the orange line in the figure 13b, is 0.155 kW. The total instantaneous power production for the month of May 2017 is 115.4 kW, while the total daily-averaged power prediction for the month of May 2017 is 4.81 kW.



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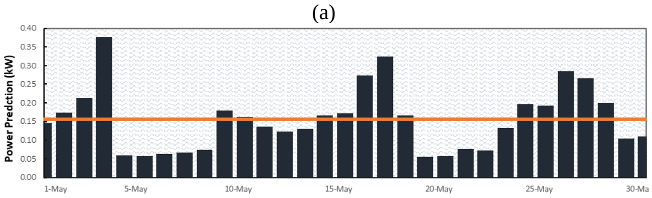
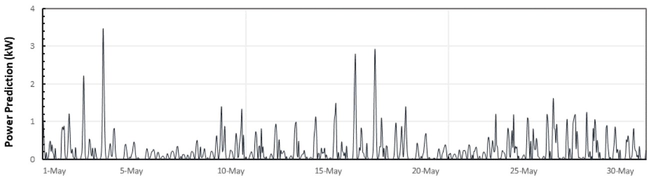


(b)

Figure 14: Power prediction of turbine rotor 1: (a) instantaneous; (b) daily-averaged.

For turbine rotor 2, the maximum instantaneous power is 3.454 kW, while the maximum daily-averaged power is 0.481 kW, and the monthly-averaged power production, seen as the orange line in figure 14b, is 0.242 kW. The total instantaneous power production for the month of May 2017 is 179.94 kW, while the total daily-averaged power prediction for the month of May 2017 is 7.5 kW.



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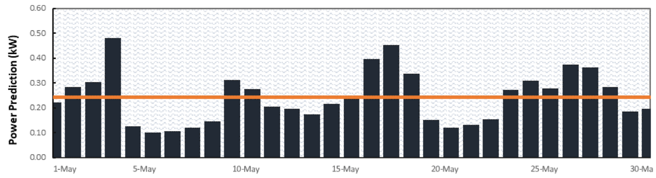

(b)

Figure 15: Power prediction of turbine rotor 2: (a) instantaneous; (b) daily-averaged.

V. CONCLUSION

For this study, the researcher was able to conduct a tidal resource assessment for the Verde Island Passage in a macro level. For the tidal parameters such as the tidal height, and tidal current, six observation points were assessed and analyzed. It is evident that the tidal parameters of the six observation points vary. It is also notable that the tidal currents of the three observations points which are tide stations, located in Anilao, Batangas Bay, and Calapan – are relatively less than the tidal currents of the other three observation points, which are located in Lobo, Tingloy, and Verde Island. The observation points in Lobo, Tingloy, and Verde Island, were chosen because those locations had high current velocities based on a preliminary simulation, while the observation points located in tide stations, were selected to validate/verify the tidal height simulation results using the tide signals.

A decision matrix using the six observation points, was created to determine the peak month of the year 2017, which was determined to be May. An energy density map was created for the peak month. Two tidal turbine rotors were simulated in an area in Verde Island Passage with a one-month period (peak month). Based on the simulation results, it is apparent that the horizontal velocities and the power production of the tidal turbine rotors are less than optimal. It should be noted that according on a study by Abundo et al. in (2011), there was a scaling effect for the simulated current velocities when comparing the simulated results to the in-situ measurement of velocities using an Acoustic Doppler Current Profiler (ADCP). It is therefore recommended to perform validation of tidal currents on the area of the study, to account for any scaling factor, if ever they are present.

APPENDICES

A. Study site parameters

The study site area limit in Verde Island passage is shown in figures 16 and 17.

In figure 16, the polyline encompasses the limit of the boundary used for the modelling. Figure 17, on the other hand, shows the total area and perimeter of the study site. The area of the study site is computed to be about 2,392.16 km^2, while the perimeter is about 423.78 km. The study site is shown as the yellow shaded region in figure 17.

Figure 16: Land boundary of study site.

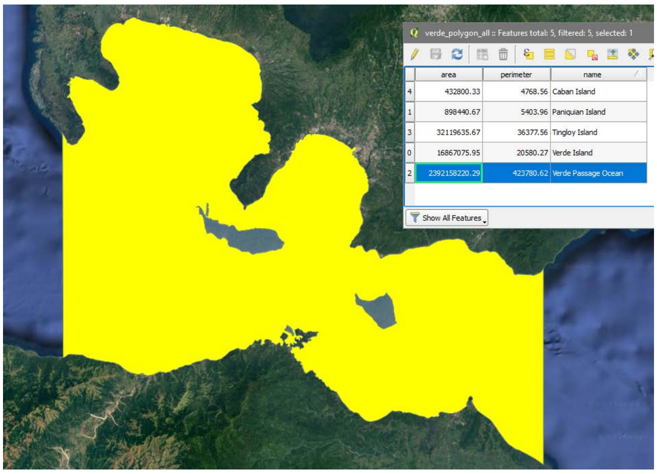

Figure 17: Area of the study site.

B. Tidal constituents used for the open boundaries

Table 3: Tidal constituents and their species and classification [18].

Name	Classification	Species
M_2	Semi diurnal	Principal lunar
S_2	Semi diurnal	Principal solar
N_2	Semi diurnal	Elliptical lunar
K_2	Semi diurnal	Declination lunar solar
K_1	Diurnal	Declination lunar solar
O_1	Diurnal	Principal lunar
P_1	Diurnal	Principal solar
Q_1	Diurnal	Elliptical lunar
M_F	Long period	Fortnightly lunar
M_M	Long period	Monthly lunar
M_4	Higher harmonics	Shallow water overtides of principal lunar
MS_4	Higher harmonics	Shallow water quarter diurnal
MN_4	Higher harmonics	Shallow water quarter diurnal

ACKNOWLEDGMENT

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