Extraction of kinetic energy in the part of Aceh Waters

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Abstract. This research is a preliminary study regarding the extraction of kinetic energy from sea tides in Aceh's waters. Aceh's waters have a reasonably long coastline (> 2000 km), which has not been studied and utilized much. The extraction of kinetic energy from ocean tides is based on the speed of currents and turbines. Hydrodynamic verification is based on sea-level data from TPXO7.2 and Geospatial Indonesia Agency (GIA). The tidal data is sufficiently consistent with the verification data from TPXO7.2 and GIA. Based on the results, the model succeeded in accurately describing the hydrodynamics currents in the research domain based on comparative verification data. The velocity of M2 tidal flow in the waters of West Aceh is relatively low, particularly in the waters of Ulee Lheue is 0.018 m/s while in Calang waters, it is 0.025 m/s. The maximum tidal energy in Ulee Lheue waters is 9,142 x 10^-2 kW, with a daily power of 4.63 x 10^3 kW. In Calang waters, the maximum energy is 2,449 x 10^-1 kW, while the daily power is 1,0167 x 10^4 kW. These results indicate that Calang Waters (Aceh Jaya district) had more significant potential for tidal currents and energy than Ulee Lheue Waters (Aceh Besar district).

1. Introduction

The waters of West Aceh are directly adjacent to the Indian Ocean so that the incoming waves are influenced by the Indian Ocean and the monsoon throughout the year [1-3]. The M2 wave is the primary tidal wave that dominates the Indian Ocean to Aceh waters. The interaction between the M2 tides to the shoreline, depth, astronomical, and meteorological factors causes M2 tides to vary in many locations [4-5]. Instead of sea-level dynamics, M2 tides generate the primary circulation in estuaries and coastal. With its capability (strong and sustainable), tidal hydrodynamics can be an alternative electric power, especially for maritime regions [6]. The need for electricity is increasing, along with the development of the population and civilization. Currently, many technologies can be developed to extract electrical energy in nature, ranging from water vapour, geothermal, solar, wind, and ocean energy [7]. The energy of tidal currents is easy to predict because they are periodic. Also, this energy relatively stable and strong compared to other natural energies, such as wind and sun [8-10]. The potential and kinetic energy are...
renewable energy that can be extracted from tides. This energy is later managed through tidal dam facilities or tidal turbines [11].

Through an exploration of tidal energy in Indonesian waters, especially the waters of Aceh, the hot spot of marine energy can be found. The West Aceh waters are close to the Indian Ocean while Aceh’s northern waters are close to the Andaman Sea and the Malacca Strait. Previous research in Aceh waters was related to current circulation due to monsoons, namely the northeast and southwest monsoons. Setiawan et al. [12] indicates that wind-driven circulation in northern Aceh waters is determined by the monsoon and bathymetric contours. Meanwhile, according to Rizal et al. [1] reported that the influence of the monsoon also affects currents in the waters west of Aceh, where the currents follow the Ekman direction and head southeast in April. Rizal et al. [13] have studied the tides, ocean currents, and general temperature in the Andaman and Malacca Strait covering western and northern Aceh waters using three-dimensional numerical models. However, the model used is a low resolution model which has limitations in more local areas such as coastal waters. Previous research has tended to discuss oceanography and has seldom examined its use.

In this study, we calculated the power or utilization of oceanography in Aceh waters by taking samples from the waters of Ulee Lheu and Calang. Aceh's waters have a reasonably long coastline that has not been yet deep explored. The study related to tidal energy of these waters will be useful as a preliminary study to support regional development.

2. Materials and Methods
This energy study uses the analyzed numerical output model of the West Aceh Waters. This model was developed by Kämpf [14] from the three-dimensional Navier-Stokes equation. In the analysis, we use used sea-level elevation and M2 tidal current from the model output. The flow of this research is as follows:

2.1. Numerical model description
The model used is based on the complete Navier-Stokes equation, which consists of equations for momentum, Coriolis force, advection, diffusion, and hydrostatic and non-hydrostatic pressure gradients. Equation (1-2) is a three-dimensional hydrodynamic equation for seawater [14]

\[
\frac{\partial u}{\partial t} + Adv(u) - f v = -\frac{1}{\rho_0} \frac{\partial (p+q)}{\partial x} + Diff(u) \\
\frac{\partial v}{\partial t} + Adv(v) + f u = -\frac{1}{\rho_0} \frac{\partial (p+q)}{\partial y} + Diff(v)
\]

where \(f\) is the Coriolis parameter, \(t\) is time, \(\rho_0\) is the density, \(u\) and \(v\) are the velocity components in the Cartesian coordinate system \((x, y)\). The topographical domain includes the waters of West Aceh, Indonesia with the research domain \((94.7\,N - 95.7\,E\) and \(4.35\,N - 5.55\,N)\) (Fig. 1). Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM30) which has been interpolated and discretized into the spatial resolution \(\Delta x = \Delta y = 2.5\,''\) and \(\Delta z = 0-5, 5-10, 10-20, 20-30, 30-50, 50-100, 100-200, 200-300, 300-500, 500-1000,> 1000\,m. In maintaining a stable calculation, we used the Courant-Friedrichs-Lewy (CFL) stability criterion for the time-step of the model (where \(t = 20\,s\)). Amplitude and tidal phase from M2 tide were used as open boundary values of the model. The data are obtained from GIA [15] (http://tides.big.go.id/pasut/konstanta/) which has spatial resolution of \(\Delta x = \Delta y = 2.5\,''\). The harmonic equation in the open boundary model is show in equation (3).

\[
\eta = A_{M2}\cos\left(\frac{2\pi}{T_{M2}} t - \varphi_{M2}\right)
\]

where \(A_{M2}\) is the amplitude of M2, \(\varphi_{M2}\) is the phase of M2, \(T\) is the M2 period \((12.42\,h)\), and \(t\) is the time (in second).
2.2. Energy analysis

For the analysis, two stations were determined to represent the Western of Aceh Waters, namely: Ulee Lheue Waters (Aceh Besar district) (95° 17' 07" E and 05° 34' 54" N) and Calang Waters (Aceh Jaya district) (95° 31' 0" E and 04° 38' 14.5" N) (Fig. 1). These two locations were determined to be areas that have observation stations and are close to the port (Table 1). Also, previous studies have examined the tides in these waters but with a low-resolution model [1] and a limited open boundary [16]. More in-depth information on the study area can be useful for further use. M2 tidal amplitude and phase are analyzed from the quarter of M2 period of tidal elevation and current circulation data by equation (4-5) [17].

\[
A = \left[ \frac{\eta^{T/4} - \eta^{3T/4}}{2} \right]^2 + \left[ \frac{\eta^T - \eta^{12}}{2} \right]^2
\]

\[
\phi = \tan^{-1} \left( \frac{\eta^{T/4} - \eta^{3T/4}}{\eta^T - \eta^{12}} \right)
\]

where \(A\) and \(\phi\) are the amplitude and phase M2, respectively. \(T\) is the tidal period for M2 (\(T = 12.42\) hours). Meanwhile, \(\eta^{T/4}, \eta^{T/2}, \eta^{3T/4}\), and \(\eta^T\) represent the sea levels or currents for each quarter of the M2 period. Amplitude and phase of sea-level M2 tide were verified using GIA data and TPXO7.2 data (https://www.tpxo.net/regional). The tidal turbine energy is calculated by equation (6). This energy
equation considers the density of seawater, the cross-sectional shape of the turbine, the resultant current velocity and the physical properties of the turbine.

\[ P = \frac{1}{2} \rho \pi R^2 V^3 C_p \]  

(6)

where \( \rho \) is the density of seawater (1024 kg/m\(^3\)), \( V^3 \) is the resultant velocity \( u \) and \( v \) (m/s), \( R \) is the radius of the cross-section (m), and \( C_p \) is the power coefficient of the kinetic energy.

### Table 1. Research domain.

| Latitude (°N) | Longitude (°E) | Location     | Depth (m) |
|--------------|---------------|--------------|-----------|
| 5.581667     | 95.285278     | Ulee Lheue   | 77.793    |
| 4.637361     | 95.516667     | Calang       | 27.084    |

### 3. Results and Discussions

#### 3.1. Model verification

We verified the hydrodynamics at Ulee Lheue and Calang stations with analysis data from BIG and TPXO7.2. Table 2 shows the amplitude and phase of sea level in Ulee Lheue waters based on model outputs, BIG, and TPXO7.2 data. The amplitude of sea-level is 0.4131 m for model output, while BIG and TPXO7.2 data are 0.4184 m and 0.4423 m, respectively. Meanwhile, the phases of sea-level are 85.3142° (model output), 83.3788° (BIG), and 82.34° (TPXO7.2). In general, the amplitude and phase from the model output are good agreement with the verification from BIG and TPXO7.2 data.

| Amplitude (m) | Phase (°) |
|---------------|-----------|
| Model Simulation | 0.4131   | 85.3142   |
| BIG           | 0.4184   | 83.3788   |
| TPXO7.2       | 0.4423   | 82.3400   |

#### Table 2. Amplitude and phase of sea-level elevation in the Waters of Ulee Lheue obtained from model output, TPXO7.2 and BIG data.

| Amplitude (m) | Phase (°) |
|---------------|-----------|
| Model Simulation | 0.1526   | 25.6563   |
| BIG           | 0.1361   | 33.7431   |
| TPXO7.2       | 0.1589   | 31.2400   |

Table 3 shows the amplitude and phase of sea level in Calang waters obtained from model output, BIG, and TPXO7.2 data. The amplitudes of sea-level are relatively the same. The amplitude of the model output is 0.1526 m, BIG is 0.1361 m, and TPXO7.2 is 0.1589 m. Meanwhile, the phase obtained from model output is 25.6563°, BIG is 33.7431°, and TPXO7.2 is 31.24°. These results indicate that the sea-level phase from the model output is different from BIG (8.0868°) and TPXO7.2 (5.5837°).
Figure 2. Sea-level elevation in the Waters of Ulee Lheue and Calang based on BIG data, TPXO7.2, and model output.

Figure 2 shows the M2 sea level from TPXO7.2, BIG, and model output in Ulee Lheue and Calang Waters. Based on continuity, sea level is closely related to ocean currents. Meanwhile, the sea level gradient determines the flow velocity and transport volume. If the sea level gradient is large, the flow velocity and transport volume become strong and vice versa [18-19]. Verification based on sea level is easier to apply because of its scalar nature and generally available verification data. The model outputs show a good agreement with the others, only in Calang waters, M2 phase slightly shifted. It is due to the resolution of the data. Model output has a high resolution; as a result, the west coast of Aceh topography and coastlines can induce more impact on the M2 phase and sea level.
3.2. $M_2$-tide power extraction

To obtain the power of the $M_2$ tide, we further analyze the current velocity at the measuring stations, namely Ulee Lheu and Calang. Figure 3, 4 and 5 show $M_2$ tidal current in the Ulee Lheue waters. The maximum of $u$-current and $v$-current are 0.019 m/s and 0.007 m/s, respectively. These velocities are then used to obtain the magnitude of the currents so that the current magnitude in Ulee Lheue waters is 0.018 m/s. Figure 6, 7, and 8 shows the velocity and the magnitude of currents in Calang waters. The maximum of $u$-current is 0.017 m/s while $v$-current is 0.02 m/s. Therefore, the magnitude of currents in Calang waters is 0.025 m/s. The tidal flow velocity in Calang waters is stronger than in Ulee Lheue waters with a difference of 0.007 m/s. It is also the same with a low resolution hydrodynamic model from Rizal et al., [1], where the semi-major of $M_2$ in Calang Waters stronger than in Ulee Lheue waters. The semi-major of $M_2$ tide describes the maximum of $M_2$ tide currents. According to Zu et al. [4], on the shallow continental shelf, the $M_2$ flow velocity is stronger than the deep basin. According to Bernoulli's theory, when the tide crosses a narrow section, the speed and kinetic energy increase while potential energy in the form of sea level decreases. In shallow waters, nonlinear effects such as advection and turbulence are quite large and have a significant impact on the power and strength of ocean currents [20-21]. Rizal and Sündermann [20] and Rizal [21] have proven that $M_2$ currents are more robust in the shallow part of the Malacca Strait (southern part). This condition is due to increased nonlinear effects of shallow waters and the complexity of the waters. It differs from deep seas where the depth contours are relatively smooth.

The current velocity is different from the wave speed, $M_2$ tides propagate more slowly in shallow waters because of the strong interaction with the bottom depth [4]. The wave speed is determined by the change in phase [4]. It can be calculated from $c = L/t$, where $c$ is the tidal wave velocity (m/s), $L$ is the distance between two adjacent phase lines or cotidal (m), and $t$ is time ($t = \triangle g T_{M2} / 360^\circ$ with $\triangle g =$ change in phase of the adjacent phase line (in degrees) and $T_{M2}$ is the $M_2$ tide period (seconds)). Based on the spatial analysis of the tidal model from Rizal et al. [1], in the waters of West Aceh waters, the phase change is $\triangle g \approx 60^\circ$ with a distance of $L \approx 3^\circ$ or 333 km so that the wave speed is $c \approx 44.77$ m/s. Meanwhile, in the northern part of Aceh waters, with $\triangle g \approx 20^\circ$ and $L \approx 333$ km, the wave speed is $c \approx 134$ m/s. It means that the wave speed is greater in northern Aceh waters such as Ulee Lheu compared to western Aceh waters such as Calang.

![U-current velocity in Ulee Lheue waters](image)

**Figure 3.** U-current of current in the Ulee Lheue waters.
The parameters used for the simulation of the M2 component tidal extraction are in Table 4. The formula used to find the tidal energy extraction power for the M2 component is in equation (6). The maximum power of the tidal currents in the waters of Ulee Lheue is \(9.142 \times 10^{-2}\) with the daily power is \(4.63 \times 10^3\). The maximum power of the tidal currents in Calang waters is \(2.449 \times 10^{-1}\) with the daily power is \(1.0167 \times 10^4\). Based on these results, the strength of the tidal currents in Calang waters is stronger than in Ulee Lheue waters (Table 5). Calang waters have a shallow depth and strong currents so that its energy more strong compared to Ulee Lheue waters. According to Rizal et al., [1], M2 tide, which is influenced by the Indian Ocean, is more significant in the shallow waters.
Figure 6. U-current of current in the Calang waters.

Figure 7. V-current of current in the Calang waters.
Figure 8. Magnitude of current in the Calang waters.

Table 4. Turbine 600 kW parameter.

| Turbine parameter | Specifications |
|-------------------|----------------|
| Generator rate power | 600 kW         |
| Power coefficient $C_p$ | 0.39           |
| Number of blade | 2              |

Table 5. The maximum power ($P$) value and daily power values in the two study sites.

| $P_{\text{maximum}}$ (kW) | Daily Power (kW) | Location |
|---------------------------|------------------|----------|
| 9.142 x 10^{-2}           | 4.63 x 10^3      | Ulee Lheue |
| 2.449 x 10^{-1}           | 1.0167 x 10^4    | Calang   |

Conclusion

The current magnitude in Ulee Lheue waters is 0.018 m/s while in Calang waters, it is 0.025 m/s. The most substantial tidal current in Ulee Lheue waters is 9.142 x 10^{-2} with a daily strength of 4.63 x 10^3. The maximum strength of tidal currents in Calang waters is 2.449 x 10^{-1} while its daily strength is 1.0167 x 10^4. Calang waters have a shallow topography, low M2-tide amplitude, and rapid in the tidal phase changes. Based on Bernoulli’s theory, shallowing and narrowing of topography and also low M2-tide amplitude contribute to stronger currents in these parts of the water [4,19-21]. Meanwhile, the intense tidal phase changes provide a small wave speed. Also, in shallow waters, nonlinear effects such as advection and turbulence are robust and have a significant impact on the power and the magnitude of currents. Therefore, the speed and strength of the current are greater in Calang Waters than in Ulee Lheue Waters. According to Alice et al. [22], the tidal current velocity must be greater than 2 m/s to obtain the potential energy of electric power. Thus, tidal power plants are not suitable to be built in the research domain.
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