Artikel 13

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Submission date: 30-Apr-2020 09:40PM (UTC+0700)

Submission ID: 1312130030

File name: ine_current_with_approach_of_a_numerical_model_for_marine....pdf (582.05K)

Word count: 4323

Character count: 20291

Study on Marine Current with Approach of a Numerical Model for Marine Current Power Plant (PLTAL) in the Bangka Strait North Sulawesi

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***Abstract*—Study on marine current with approach of a numerical model for marine current power plant (PLTAL) in the Bangka strait North Sulawesi has been investigated. Construction of power plant is needed to overcome the shortage of electricity in North Sulawesi. Before building the electrical energy it would require a feasibility study which aim to ensure the certainty of the construction of power plant. One of them is through the study of marine currents in the design of a numerical model. The objective of this investigates for long-term to get a profile of marine current turbines as one component in the construction of marine current power plant in the Bangka strait. Specific targets to achieve are to get the first; data such as tide, sea water and air temperature on the surface, the wind speed above sea level, a map of the Bangka Strait and bathymetry, the second; a design of numerical model and kinetic energy distributions. The method used was initially literature study, survey in the research location, measurements of data such as tide, temperatures of sea water and the air above the surface, wind speed above sea level, bathymetry of the Bangka strait, finally are the analysis of data measurements and design of a numerical model in the form of numerical program. The results showed that the data tide from January 16 until February 21, 2016 the maximum and minimum of 2.4 m and 0.3 m respectively that oscillates to datum line of 1.2 m. Numerical program developed from the semi implicit finite difference method for shallow water in two and three dimension by the basis algorithm that consists of three fractional steps are advection step, diffusion step, and pressure-continuity step. The numerical program will be a product in analyzing potential kinetic energy as the prime mover of turbines for marine current power plant in the Bangka strait.**

***Keywords*—numerical modeling; numerical simulation; marine current turbines; PLTAL**

I. Introduction

Development of electricity power plant is a part of a whole development in North Sulawesi because the electricity consumption would go up along with the increasing of public activity and a prosperous people (as the economy has grown rapidly in North Sulawesi the last years, so has the demand for electricity). Public utilizes electricity for many purpose such as household requirement as well as economics trade. Therefore supplying adequate amount of electricity and existence of continuities electricity power should help to maintain conducive social and economic activity, and to motivate public economic growth. When the electricity is insufficient, the electricity power will be put out to balance the supply for consumer. Putting out of electricity has been occurring several times in North Sulawesi, this case has influenced by the development and investment.

The ideal locations for power station installation of the current energy have velocities of current two directions (minimum bidirectional) 2 m/s [12]. The ideal is 2.5 m/s or more. One way (river/current of geotropic) is minimum 1.2-1.5 m/s. The deepness not less than 15 m and the most at 40 or 50 m. Close to coast so that energy can be channeled with low expense. They have add for wide that more than one turbine can be attached, not sea transport and the fish arrest area.

A numerical model of marine currents in Bangka strait used a semi-implicit finite difference method for the numerical solution of three-dimensional shallow water flows. Several numerical methods with solution of shallow water equations are used in practical applications [3], [4], [7]. In semi-implicit methods only the barotropic pressure gradient in the momentum equations and the velocity divergence in the continuity equation are taken implicitly. Each time step a linear five-diagonal system is solved in the new water surface elevations for the entire domain are the unknowns. The model is generally explicit with the exception that the vertical eddy viscosity terms are discretized implicitly. In the model formulation the governing system of equations is split into an external and an internal mode [2]. Momentum exchanges between vertical layers are expressed in a set of tri-diagonal matrix equations relating the discrete horizontal velocities in each vertical level to the gradient of the water surface elevations [11]. A formal expression for the solution of these tri-diagonal systems can be written in terms of the barotropic pressure gradient. Substituting the formal solutions in the vertically integrated continuity equation gives rise to a linear five-diagonal system whose only unknowns are the water surface elevation over the domain of interest. Such a system is symmetric and positive definite and can be solved uniquely and efficiently by using a conjugate gradient method. By direct substitution of the barotropic pressure gradient known at the advanced time level, the horizontal velocity for each vertical layer can be computed. The vertical velocity component can be found by integration of the continuity equation. This paper is more majoring to study the velocities of current and know the availability of kinetic energy in the Bangka Strait. This study is intended for the installation of turbines in the place more adapted strait in order to provide electrical current to the close environment.

The objective of this investigates for long-term is to get a profile of marine current turbines as one component in the construction of marine current power plant in the Bangka strait. Specific targets to achieve are to get the first; data such as tide, sea water and air temperature on the surface, the wind speed above sea level, a map of the Bangka Strait and bathymetry, the second; a design of numerical model and kinetic energy distributions.

II. Model Equations

A. Basic equations

Under the assumptions of hydrostatic pressure, and by using the decomposition of preceding Reynolds, the realized average Navier-Stokes equations are written [6]:

Continuity equation

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z} = 0 \qquad (1)$$

Momentum equation

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial y} + \overline{w}\frac{\partial \overline{u}}{\partial z} = -g\frac{\partial \eta}{\partial x} + div\left(\nu_{eff}\,\overrightarrow{grad}(\overline{u})\right) + f_{cor}\overline{v} \qquad (2)$$

$$\frac{\partial \overline{v}}{\partial t} + \overline{u}\frac{\partial \overline{v}}{\partial x} + \overline{v}\frac{\partial \overline{v}}{\partial y} + \overline{w}\frac{\partial \overline{v}}{\partial z} = -g\frac{\partial \eta}{\partial y} + div\left(\nu_{eff}\,\overrightarrow{grad}(\overline{v})\right) - f_{cor}\overline{u} \qquad (3)$$

Free surface equation

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\left(\int_{-h}^{\eta}\overline{u}\,dz\right) + \frac{\partial}{\partial y}\left(\int_{-h}^{\eta}\overline{v}\,dz\right) = 0 \qquad (4)$$

Where, ν_{eff} is an effective diffusion taking of account turbulent viscosity and dispersion $\nu_{eff} = \nu + \nu_t$. This effective diffusion is given by means of a model of turbulence adapted to the problem considers. Equation (1) to (4) will be those considered in the continuation of the report.

Power is just energy divided by time, so the power available from the seawater current [13]-[17] can be expressed as:

$$P = \frac{E_k}{dt} = \frac{1}{2}\rho . v^3 . A \qquad (5)$$

Where, P is the power available from the seawater current in Watt.

In this study we will calculate the power of marine current in the Bangka strait per unit cross-sectional area (m^2), thus, from equation 5 we can be obtain:

$$P_A = \frac{P}{A} = \frac{1}{2}\rho\, v^3 10^{-3} \qquad (6)$$

Where, P_A is the power per cross-sectional area in kW/m^2 and v is the velocity resultant of marine current that defined as $v = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}$ with $\overline{u}$, $\overline{v}$ and $\overline{w}$ respectively are scalars of the velocities $\overline{u}$, $\overline{v}$ and $\overline{w}$ respectively, and $\rho = 1024$ kg/m^3 [18] (at 20 (C) and salinity of 34).

B. Turbulence model

A formula for turbulent viscosity is the standard form as defined from the mixing-length model with assuming $(\partial w/\partial z)^2 \ll (\partial u/\partial x)^2 + (\partial v/\partial y)^2$, $\partial w/\partial y \ll \partial v/\partial z$ and $\partial w/\partial x \ll \partial u/\partial z$ for shallow water flows where vertical velocity w is small was used by Stansby [9] and Cea [4]. The eddy viscosity is computed at each point from the horizontal and vertical component velocity gradients and length scales for horizontal and vertical motion, giving a formula for turbulent viscosity as:

$$\upsilon_t = \sqrt{\left(l_h^4\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2\right] + l_v^4\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]\right)} \qquad (7)$$

for $l_v = \kappa(z-z_b)$, for $(z-z_b)/h < \lambda/\kappa$; $l_v = \lambda h$, for $\lambda/\kappa < (z-z_b)/h < 1$; and $l_h = \beta\, l_v$, for the horizontal length scale is larger; where κ is the von Karman's constant ($\kappa = 0.41$), λ is a constant ($\lambda = 0.09$), $(z-z_b)$ is the distance from the wall, h is the boundary layer thickness assumed to be equal to the water depth, l_v and l_h are the vertical and horizontal length scales, and the constant β has to be determined from comparison with experiment.

C. Boundary conditions

For the problem studied in this paper, some types of boundary conditions are required. These are imposed as follows: (i) the boundary conditions at the free surface are specified by the prescribed wind stresses of directions x and y, and a slip boundary $\partial u/\partial z = \partial v/\partial z = 0$; (ii) the boundary conditions at the bottom stress can be related to the turbulent law of the wall, a drag coefficient associated with using a Chezy formula [2]; (iii) the boundary conditions for velocity on a solid wall is a no-slip condition [6], and on the open boundary, we used principally two condition, the first is Neumann method and the second is a condition radiation which derived from Orlanski's algorithm [10].

III. NUMERICAL MODEL

Semi-implicit finite difference method for the numerical solution of the three-dimensional in (1) to (4) was used by Casulli & Cheng [2], Stansby [8], and Chen [5] in the computation of shallow water flows. Equation (2) and (3) will be derived in which the gradient of surface elevation in the momentum equations and the velocity in the free surface in (4) will be discretized implicitly. The convective, Coriolis and horizontal viscosity terms in the momentum equations will be discretized explicitly, but in order to eliminate a stability condition due to the vertical eddy viscosity, the vertical mixing terms will be discretized implicitly.

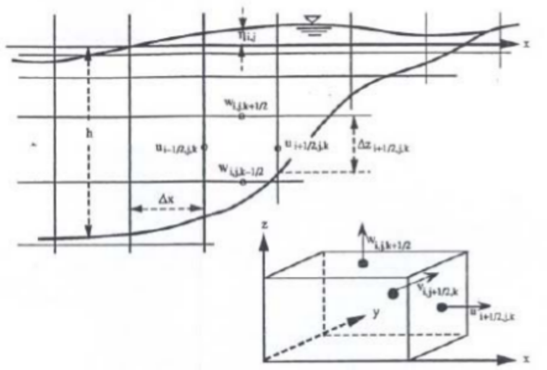

Fig. 1. Schematic diagram of computational mesh and notations

Fig. 1 shown that a spatial mesh which consists of rectangular cells of length Δx, width Δy and height Δz_k is introduced. Each cell is numbered at its centre with indices *i, j* and *k*. The discrete *u*-velocity is then defined at half-integer *i, j* and *k*; *v* is defined at integers *i*, k, and half-integer *j*; *w* is defined at integers *i*, *j* and half-integer *k*. Then η is defined at integers *i* and *j*. The water depth *h(x,y)* is specified at the *u* and *v* horizontal points. So that a general semi-implicit discretization of the momentum equations in (2) and (3) can be written in the more compact matrix form as

$$\mathbf{A}^{n}_{i+1/2,j}\mathbf{U}^{n+1}_{i+1/2,j} = \mathbf{G}^{n}_{i+1/2,j} - g\frac{\Delta t}{\Delta x}\left(\eta^{n+1}_{i+1,j} - \eta^{n+1}_{i,j}\right)\mathbf{\Delta Z}^{n}_{i+1/2,j} \quad (8)$$

$$\mathbf{A}^{n}_{i,j+1/2}\mathbf{V}^{n+1}_{i,j+1/2} = \mathbf{G}^{n}_{i,j+1/2} - g\frac{\Delta t}{\Delta y}\left(\eta^{n+1}_{i,j+1} - \eta^{n+1}_{i,j}\right)\mathbf{\Delta Z}^{n}_{i,j+1/2} \quad (9)$$

where **U**, **V**, **ΔZ**, **G** and **A** are defined as:

$$\mathbf{U}^{n+1}_{i+1/2,j} = \begin{bmatrix} u^{n+1}_{i+1/2,j,M} \\ u^{n+1}_{i+1/2,j,M-1} \\ u^{n+1}_{i+1/2,j,M-2} \\ \vdots \\ u^{n+1}_{i+1/2,j,m} \end{bmatrix},$$

$$\mathbf{V}^{n+1}_{i,j+1/2} = \begin{bmatrix} v^{n+1}_{i,j+1/2,M} \\ v^{n+1}_{i,j+1/2,M-1} \\ v^{n+1}_{i,j+1/2,M-2} \\ \vdots \\ v^{n+1}_{i,j+1/2,m} \end{bmatrix}, \quad \mathbf{\Delta Z} = \begin{bmatrix} \Delta z_M \\ \Delta z_{M-1} \\ \Delta z_{M-2} \\ \vdots \\ \Delta z_m \end{bmatrix},$$

$$\mathbf{G}^{n}_{i+1/2,j} = \begin{bmatrix} \Delta z_M Fu^{n}_{i+1/2,j,M} + \Delta t\,\tau^{w}_{x} \\ \Delta z_{M-1} Fu^{n}_{i+1/2,j,M-1} \\ \Delta z_{M-2} Fu^{n}_{i+1/2,j,M-2} \\ \vdots \\ \Delta z_m Fu^{n}_{i+1/2,j,m} \end{bmatrix},$$

$$\mathbf{G}^{n}_{i,j+1/2} = \begin{bmatrix} \Delta z_M Fv^{n}_{i,j+1/2,M} + \Delta t\,\tau^{w}_{y} \\ \Delta z_{M-1} Fv^{n}_{i,j+1/2,M-1} \\ \Delta z_{M-2} Fv^{n}_{i,j+1/2,M-2} \\ \vdots \\ \Delta z_m Fv^{n}_{i,j+1/2,m} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} \Delta z_M + \frac{\nu_{M-1/2}\Delta t}{\Delta z_{M-1/2}} & \frac{-\nu_{M-1/2}\Delta t}{\Delta z_{M-1/2}} & & 0 \\ \frac{-\nu_{M-1/2}\Delta t}{\Delta z_{M-1/2}} & \Delta z_M + \frac{\nu_{M-1/2}\Delta t}{\Delta z_{M-1/2}} + \frac{\nu_{M-3/2}\Delta t}{\Delta z_{M-3/2}} & \frac{-\nu_{M-3/2}\Delta t}{\Delta z_{M-3/2}} & \\ \vdots & \vdots & \vdots & \vdots \\ 0 & & \frac{-\nu_{m-1/2}\Delta t}{\Delta z_{m-1/2}} & \Delta z_m + \frac{\nu_{m+1/2}\Delta t}{\Delta z_{m+1/2}} + \frac{g\Delta t\sqrt{(u^2+v^2)}}{C_z^2} \end{bmatrix}$$

Where *m* and *M* denote the *k*-index of the bottom and the top finite difference stencil respectively, C_z is the Chezy's friction coefficient, τ^{w}_{x} and τ^{w}_{y} are wind stresses, and *F* is non-linear finite difference operator and an explicit.

Equation (8) and (9) are linear tri-diagonal systems. For determine the free surface $\eta^{n+1}_{i,j}$ as in (4) can be written in the matrix notation form

$$\eta^{n+1}_{i,j} = \eta^{n+1}_{i,j} - \frac{\Delta t}{\Delta x}\left[\left(\mathbf{\Delta Z}_{i+1/2,j}\right)^{T}\mathbf{U}^{n+1}_{i+1/2,j} - \left(\mathbf{\Delta Z}_{i-1/2,j}\right)^{T}\mathbf{U}^{n+1}_{i-1/2,j}\right] - \frac{\Delta t}{\Delta y}\left[\left(\mathbf{\Delta Z}_{i,j+1/2}\right)^{T}\mathbf{V}^{n+1}_{i,j+1/2} - \left(\mathbf{\Delta Z}_{i,j-1/2}\right)^{T}\mathbf{V}^{n+1}_{i,j-1/2}\right] \quad (10)$$

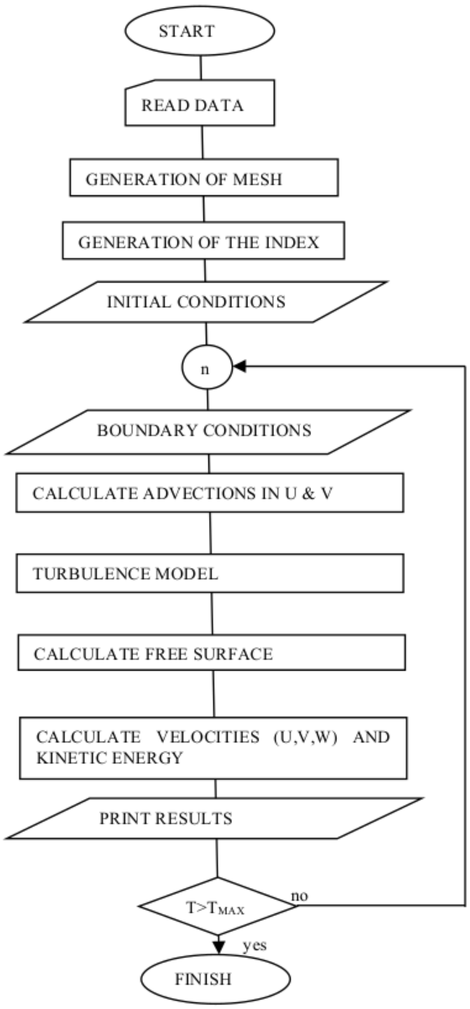

Fig. 2. Flow chart of a numerical model

The vertical component of the velocity w at the new time level can be discretized from the continuity as in (1) becomes:

$$\overline{w}_{i,j,k+1/2}^{n+1} = \overline{w}_{i,j,k-1/2}^{n+1} - \frac{\Delta z_{i+1/2,j,k}^{n}\overline{u}_{i+1/2,j,k}^{n+1} - \Delta z_{i-1/2,j,k}^{n}\overline{u}_{i-1/2,j,k}^{n+1}}{\Delta x} - \frac{\Delta z_{i,j+1/2,k}^{n}\overline{v}_{i,j+1/2,k}^{n+1} - \Delta z_{i,j-1/2,k}^{n}\overline{v}_{i,j-1/2,k}^{n+1}}{\Delta y} \quad (11)$$

Where, $k=m$, $m+1...M$, and the no-flux condition across the bottom boundary is assumed by taking $\overline{w}_{i,j,m-1/2}^{n+1} = 0$.

The available energy that investigated in this study is the available power per m^2 (kW/m^2). The first, we will back at the equation of the available power which is equation of the marine current power in the Bangka strait can be discretized from (6) become:

$$P_A = \frac{P}{A} = \frac{1}{2}\rho\ (\mathrm{v}_{i,j,k}^{n+1})^3 10^{-3} \quad (12)$$

Where P_A is the marine current power (kinetic energy) in the Bangka strait in kW/m^2 and $\mathrm{v}_{i,j,k}^{n+1} = \sqrt{\overline{\mathrm{u}}^2 + \overline{\mathrm{v}}^2 + \overline{\mathrm{w}}^2}$ is velocity resultant with $\overline{\mathrm{u}} = \frac{1}{2}(\overline{u}_{i,j,k}^{n+1} + \overline{u}_{i+1,j,k}^{n+1})$, $\overline{\mathrm{v}} = \frac{1}{2}(\overline{v}_{i,j,k}^{n+1} + \overline{v}_{i,j+1,k}^{n+1})$, and $\overline{\mathrm{w}} = \frac{1}{2}(\overline{w}_{i,j,k}^{n+1} + \overline{w}_{i,j,k+1}^{n+1})$ are scalars, respectively.

IV. RESEARCH METHOD

The method used was initially literature study; survey in the research location; measurements of data such as tide (January and February, 2016), temperatures of sea water and the air above the surface, wind speed above sea level; bathymetry of the Bangka strait; finally are the analysis of data measurements and design of a numerical model in the form of numerical program.

Fig. 2 shows steps of a numerical model in calculating the velocities of $\overline{u}$, $\overline{v}$ and $\overline{w}$ respectively and the power of marine current in the Bangka strait per cross-sectional area.

V. RESULTS AND DISCUSSION

The Bangka strait is located between the Pacific Ocean and the Sulawesi sea whose area is approximately 200 km^2 (Fig. 4), with a minimum width between Sahaong foreland (in Bangka island) and Mokotamba foreland (in Likupang town) about 5.5 km and down to 69 meters deep (the average depth of 40 m).

The three-dimensional current circulation in the Bangka strait is simulated using the present model with a 174 x 318 finite difference mesh of equal $\Delta x = \Delta y = 60$ m. The numerical solutions have been achieved using four vertical layers and an integration time Δt = 1 sec, and inlet volume transports at sections A and B (see Fig. 4) are 0.025 Sv, 0.1 Sv, 0.3 Sv and 0.5 Sv.

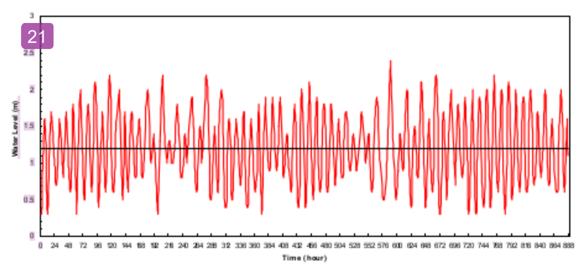

Fig. 3. Tides measurement results of the Bangka strait

Fig. 3 shows a result of the tide measurements in the Bangka strait from January 16 to February 21, 2016. The types of tides are mixed type, in particular semidiurnal type and diurnal type was only occurred on February 9. The tidal range variations were taken place between 0.3 m to 1.9 m. The tidal period variations were between 10 h to 20 h. The maximum and minimum of 2.4 m and 0.3 m respectively that oscillates at datum line of 1.2 m. The tides data were obtained by direct monitoring of water level (1 h intervals) using a tide gage. The first day measurement on January 16, 2016 was started at 01.00 am until 00.00 pm. Measurements of tide on second days until days 37th were performed as the first day measurement. The results of tide measurement on January 18, 2016 which lower low water at level 0.3 m and highest high water at level 2 m, while higher low water at 0.6 m and lower high water at 1.8 m. The variation tidal range was obtained at 1.2 m to 1.7 m. The minimum tidal range was occurred at 03.00 am to 08.00 am at level 1.2 m and a maximum that occurred at 02.00 pm to 08.00 pm at level 1.7 m. The variation tidal period was taken place between 11 to 12 hours. The minimum wave period was occurred during 11 hours at 03.00 am to 02.00 pm and a maximum was occurred during 12 hours at 08.00 am to 08.00 pm.

In the 3D-simulations, we also have made two types of simulations with four variation of discharge. The first type, we also have conducted when low tide current where each simulation has considerate with constant discharge inside. In second type, when high tide currents with same condition discharge as in first simulations. Parameter of entry discharge, we also have made variation from 0.025 Sv to 0.5 Sv with classifications are 0.025 Sv, 0.1 Sv, 0.3 Sv and 0.5 Sv (1 Sv = 1x10^6 m^3/s). For the other parameter, we can see in table 1. Measurement results in the area of numerical such as temperatures of sea water (T_{water}) and the air above the surface (T_{air}) of 20 C and 29 C respectively.

Fig. 5 illustrates the bathymetry of the Bangka strait used for numerical simulation. The water depth distributions show the complex areas where maximum depth of 69 m (between Bangka island and Likupang town).

TABLE I. NUMERICAL PARAMETER FOR 3D-SIMULATION

Parameter	Value	Parameter	Value
g	9.81 m s^{-2}	$\rho_{seawater}$	1024 kg/m^3
Cz	48	Δx	60 m
τ_o	2 days	Δy	60 m
τ_i	1 day	Δz	20 m
Discharge	variable	Δt	1 sec
T_{water}	20 C	T_{air}	29 C

The distributions of the available power per m^2 (kinetic energy) when low tide currents (3D-simulation) shown in Fig. 6. Discharge influence to the available power is very big where ever greater of discharge then ever greater also power availability like in 2D-simulation. At discharge of 0.025 Sv (a) shows that there are about 1.5-5 W/m^2 available in around section A (see Fig. 4), whereas 5-350 W/ m^2 at 0.1 Sv (b), 0.5-10 kW/ m^2 at 0.3 Sv (c) and at 0.5 Sv (d) available of 1-45 kW/m^2 which is maximum discharge.

Also, when high tide currents in Fig. 7, we found around section A where the power availabilities per m^2 are maximal. Generally, there are about 2-9 W/m^2 at 0.025 Sv (a), 5-550 W/m^2 at 0.1 Sv (b), 0.5-16 kW/m^2 at 0.3 Sv (c) and 1-77 kW/m^2 at 0.5 Sv (d) power availabilities per m^2 in the Bangka strait which the values are bigger than in Fig. 6. We also can see that the two when low and high tide currents where can be concluded that biggest values are at section A.

Fig. 4. Location of the Bangka strait in Indonesia and numerical area

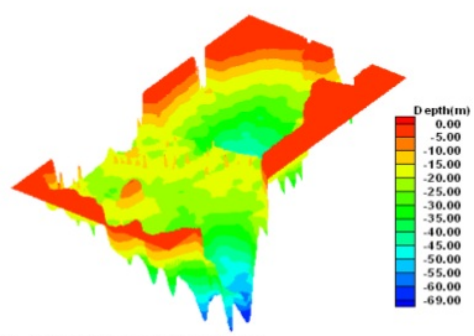

Fig. 5. Bathymetry of the Bangka strait

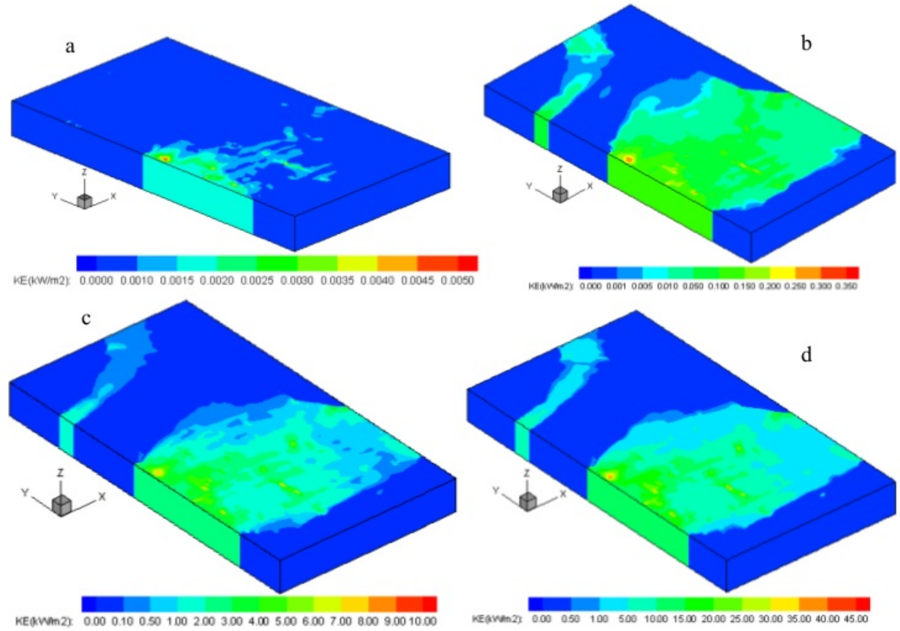

Fig. 6. Simulated (3D) distributions of the available power per m^2 at seawater column of 20 m when low tide currents at (a) discharge 0.025 Sv, (b) discharge 0.1 Sv, (c) discharge 0.3 Sv and (d) discharge 0.5 Sv.

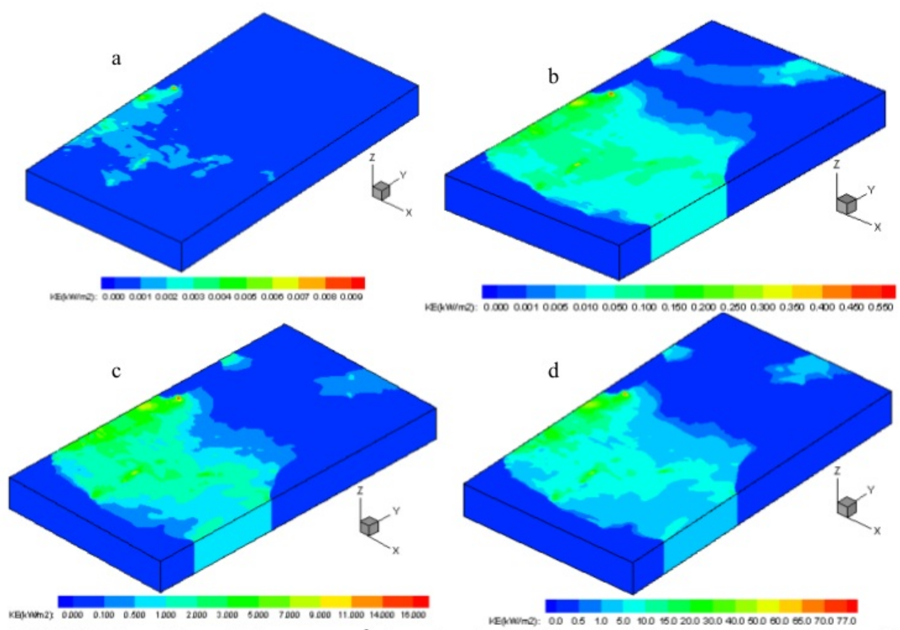

Fig. 7. Simulated (3D) distributions of the available power per m^2 at seawater column of 20 m when high tide currents at (a) discharge 0.025 Sv, (b) discharge 0.1 Sv, (c) discharge 0.3 Sv and (d) discharge 0.5 Sv.

The results showed that the numerical program will be a product in analyzing potential kinetic energy as the prime mover of turbines for marine current power plant in the Bangka strait.

VI. Conclusions

A numerical semi-implicit finite difference models for the study marine currents in the Bangka Strait has been presented. The numerical program will be a product in analyzing potential kinetic energy as the prime mover of turbines for marine current power plant in the Bangka strait. When low tide currents, available from 0.5 W/ m^2 until 45 kW/m^2 and from 0.5 W/m^2 until 77 kW/m^2 at high tide currents. The values obtained by calculations will be enabling to choose a suitable place for installing the turbines adapted well for a future undersea electricity power plant in the Bangka strait.

Acknowledgment

The authors wish to express their appreciation to Kemristekdikti of the Republic of Indonesia which had financed all of the research activities, and Rector of Manado State University, Indonesia who has proposed research grant.

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