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Numerical simulation of marine currents in the Bunaken Strait, North Sulawesi, Indonesia

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Abstract. This study intended for the generation of hydroelectric power at suitable area of the strait in order to provide electric current to a close environment. The project uses a three-dimensional model of taking flow into account the variation of hydrostatic pressure in the liquid vertical layers. We brought back to a two-dimensional calculation using the shallow water equations. The objectives of the study are getting simultaneous obtaining the velocities of currents by the component of velocities and distributions of the kinetic energy from the numerical results. The Bunaken strait is 5280 m width for an average depth of 130 m. Numerical calculation is simulated using horizontal meshes of 60 side meters. The numerical solutions obtained by using a time step of one second. It found that there was no great difference between 2D and 3D numerical simulations because the effect of flow velocity in the vertical direction is very small. The numerical results have shown that the average current velocities when low and high tide currents are 1.46 m/s and 0.85 m/s respectively. The kinetic energy ranged from 0.01 to 2.54 kW/m^2 when low and high tide in the Bunaken strait area at discharge of 1 Sv, whereas at discharge 2 Sv, 0.11-17.40 kW/m^2 and 0.11-2.77 kW/m^2 (when low and high tide currents). These results can used in the design of turbines for power generation marine currents in the Bunaken strait at depths below 60 meters.

1. Introduction

Construction of electrical power plants in Indonesia is urgently needed to overcome the shortage of electrical energy to date. One of the components for the construction of the power plant is marine current turbine [8, 9]. Marine current turbine designs requiring variable of current velocity which is directly proportional to the kinetic energy. Many ways to get the data of current velocity, one way is by numerical model [2]. A numerical model of marine currents in Bunaken 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 used in practical applications [1, 2, 3, 5]. Several existing numerical model for two and three dimensional shallow water flow simulations based on an alternating direction implicit ADI method. In semi-implicit method, only the *barotropic* pressure gradient in the momentum equations and the velocity divergence in the continuity equation taken implicitly. Each time step a linear five-diagonal system solved in new the water surface elevations for the entire domain are the unknowns. The model is generally explicit with the exception that the vertical eddy viscosity terms discretized implicitly. In the model formulation, the governing system of equations split into an external and an internal mode [2]. Momentum exchanges between vertical layers 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 [5].

This paper is more majoring to study the velocities of current and know the availability of kinetic energy in the Bunaken Strait. In addition, intended for the installation of marine current turbine in the place more adapted strait in order to provide electrical current to the close environment.

The objectives of the study are getting simultaneous obtaining the velocities of currents by the component of velocities and distributions of the kinetic energy from the numerical results.

2. Experimental Setup

2.1 Mathematical Model

The model of three-dimensional equations that developed from the Navier-Stokes equations after turbulent averaging and under assumption that the pressure is hydrostatic [2, 3], the equations as follow:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-g\frac{\partial \eta}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\upsilon_t\frac{\partial u}{\partial z}\right)+f.v \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-g\frac{\partial \eta}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\upsilon_t\frac{\partial v}{\partial z}\right)+f.u \tag{2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

where *u(x,y,z,t), v(x,y,z,t),* and *w(x,y,,z,t)* are the velocity components in the directions represent *x, y,* and *z* respectively,
η(x,y,t) is the free surface, *t* is the time, μ and υ_t are the eddy viscosity coefficients of horizontal and vertical respectively,
f is the Coriolis parameter, assumed to be constant,
And *g* is the constant gravitational acceleration.

The current computing power does allow taken into the account direct one by using the Reynolds Average Navier-Stokes Equations (RANS) [1].

2.1.1. Turbulence model.

A formula for turbulent viscosity is the standard form as defined:

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

Where: $l_v = \kappa(z-z_b)$, for $(z-z_b)/h < \lambda/\kappa$;
$l_v = \lambda h$, for $\lambda/\kappa < (z-z_b)/h < 1$, for $l_h = \beta\ l_v$, for the horizontal length scale is larger, κ is the von Karman's constant (κ = 0.41), λ is a constant (λ = 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,
In addition, the constant β has to be determined from comparison with experiment.

2.1.2. Boundary condition.

Some types of boundary conditions are required as the boundary conditions at the free surface are specified by the prescribed wind stresses of directions *x* and *y*, and a slip boundary $\partial u/\partial z=\partial v/\partial z=0$. At the bottom stress can be related to the turbulent law of the wall, a drag coefficient associated with using a Chezy formula [2]. Velocity on a solid wall is a no-slip condition, 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 that developed by Treguier *et al*. [4].

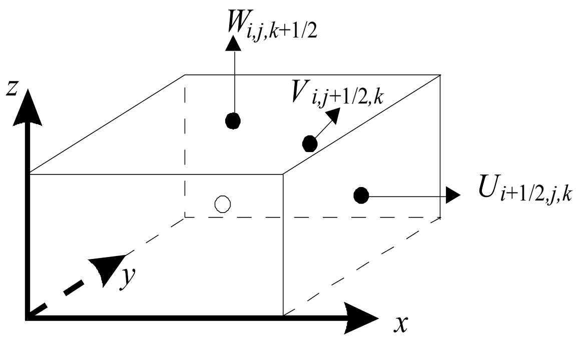
The kinetic energy in the Bunaken strait (P_A), we can be obtaining from equation [6]:

$$P_A = \frac{P}{A} = \frac{1}{2}\rho \, \mathrm{v}^3 10^{-3} \tag{5}$$

Where P_A in kW/m^2, v is the velocity resultant of marine current (m/s) and ρ is seawater density (kg/m^3).

2.2 Numerical Model

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



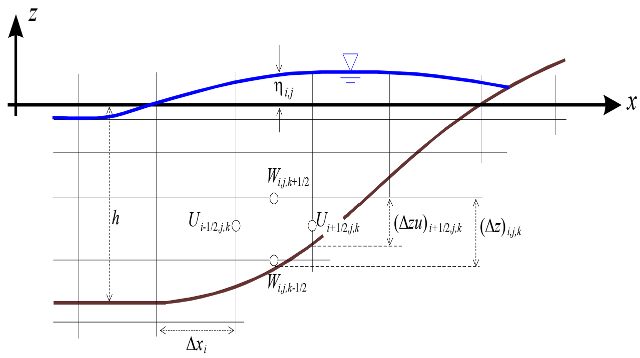


Figure 1. Schematic diagram of computational mesh and notations

Figure 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*. Figure 1 (a) show that 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 figure 1 (b) show that 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 Equation 1 and Equation 2 can be written in the more compact matrix form as

$$\mathbf{A}^n_{i+1/2,j}\mathbf{U}^{n+1}_{i+1/2,j} = \mathbf{G}^n_{i+1/2,j} - g\frac{\Delta t}{\Delta x}\left(\eta^{n+1}_{i+1,j} - \eta^{n+1}_{i,j}\right)\mathbf{\Delta Z}^n_{i+1/2,j} \tag{6}$$

$$\mathbf{A}^n_{i,j+1/2}\mathbf{V}^{n+1}_{i,j+1/2} = \mathbf{G}^n_{i,j+1/2} - g\frac{\Delta t}{\Delta y}\left(\eta^{n+1}_{i,j+1} - \eta^{n+1}_{i,j}\right)\mathbf{\Delta Z}^n_{i,j+1/2} \tag{7}$$

Equation 6 and Equation 7 are linear tri-diagonal systems. For determine the free surface $\eta^{n+1}_{i,j}$ can be written in the matrix notation form

$$\begin{aligned}\eta^{n+1}_{i,j,} = \eta^{n+1}_{i,j,} &- \frac{\Delta t}{\Delta x}\left[\left(\mathbf{\Delta Z}_{i+1/2,j}\right)^{\mathrm{T}}\mathbf{U}^{n+1}_{i+1/2,j} - \left(\mathbf{\Delta Z}_{i-1/2,j}\right)^{\mathrm{T}}\mathbf{U}^{n+1}_{i-1/2,j}\right] \\ &- \frac{\Delta t}{\Delta y}\left[\left(\mathbf{\Delta Z}_{i,j+1/2}\right)^{\mathrm{T}}\mathbf{V}^{n+1}_{i,j+1/2} - \left(\mathbf{\Delta Z}_{i,j-1/2}\right)^{\mathrm{T}}\mathbf{V}^{n+1}_{i,j-1/2}\right]\end{aligned} \tag{8}$$

The available energy that investigated in this study is the kinetic energy (kW/m^2). The first, we will back at the equation of the kinetic energy which is equation of the marine current power in the Bunaken strait can be discretized from Equation 5 becomes:

$$P_A = \frac{P}{A} = \frac{1}{2}\rho\ (\mathrm{v}_{i,j,k}^{n+1})^3 10^{-3} \tag{9}$$

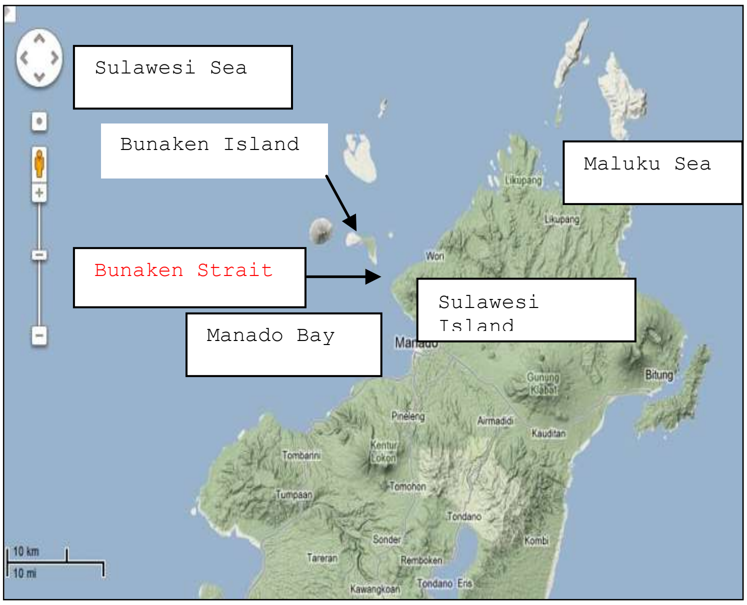
3. Results and Discussion

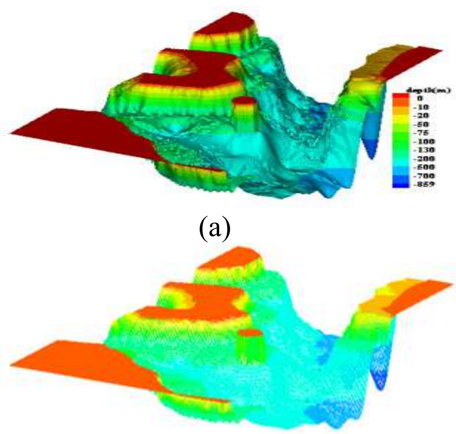
3.1. The Domain Presentation of the Bunaken Strait

The Bunaken strait is located between the Pacific ocean and the Sulawesi sea (Celebes sea) whose area is approximately 200 km^2 (Figure 2), with a minimum width between Bunaken island and Sulawesi island about 5.28 km and the average depth of 130 m.

The three-dimensional current circulation in the Bunaken strait is simulated using the present model with 174 x 318 x 4 finite difference meshes of equal $\Delta x = \Delta y = 60$ m and $\Delta x = 20$ m. The numerical solutions used an integration time $\Delta t = 1$ sec and inlet volume transports (discharges) are 1 Sv to 2 Sv (1 Sv = 10^6 m^3s^{-1}). Figure 3 illustrates the bathymetry (a) and the meshes (b), the 3D of the Bunaken strait used for numerical simulation. The water depth distributions show the complex areas.

Currents in the Bunaken strait closely related with ocean currents and Indonesian throughflow. According to Brown *et al*. [7] that the global wind system would be if the Earth were completely covered with water, and the atmospheric circulation transports heat from low to high latitudes and the same is true in the oceans, where surface currents warmed in low latitudes carry heat polewards, while currents cooled at high latitudes flow equatorwards. Marine currents in the Bunaken strait consist of two i.e. high tide currents and low tide currents. In the morning, occurred high tide currents where input currents from from Maluku Sea (see right of Figure 2). The currents then go out to Manado bay and then they go out to Sulawesi Sea. In the evening, occurred low tides currents that are inversed on obtaining of high tide currents. The currents obtain from Sulawesi Sea and Manado bay. The currents then go inside pass in the left of Bunaken strait. Then the currents go out to the right of Bunaken strait and then go out to Maluku Sea.





(a)

(b)

Figure 3. The 3D of the Bunaken strait with water depth: (a) Bathymetry and (b) Meshes.

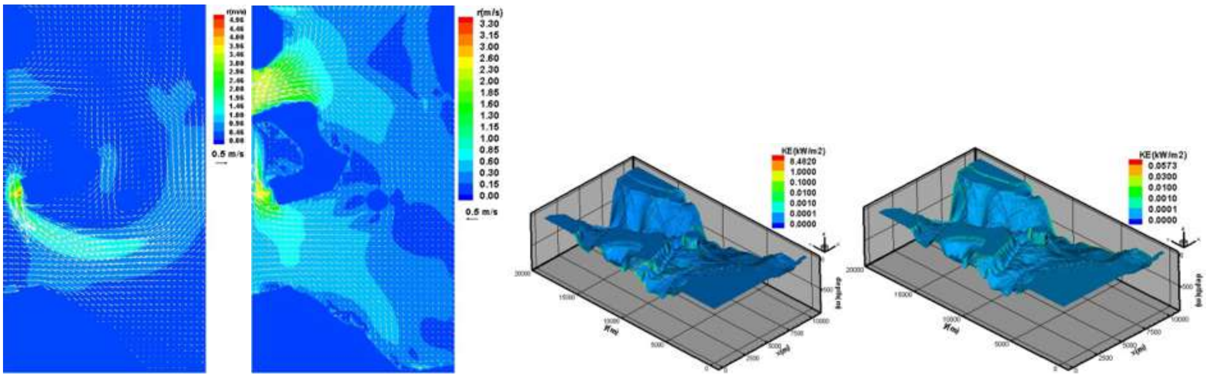
Figure 2. Location of the Bunaken strait in North Sulawesi, Indonesia.

In 2D simulations, we made two type of simulations with two variations of discharge. In first simulation, we have conducted when low tide current where each simulation has considerate with constant discharge inside. In second simulation, when high tide currents with condition discharge same as in first simulation. Parameter of discharge varies from 1 to 2 Sv with classifications are 1 Sv and 2 Sv.

Like in 2D simulations, 3D simulations we also have made two type of simulations with two variations of discharge. In 3D simulations, there are 4 layers of seawater column which each layer depth of 20 m (Δz), respectively. Whereas in 2D simulations only one layer of seawater column which layer depth is maximum depth.

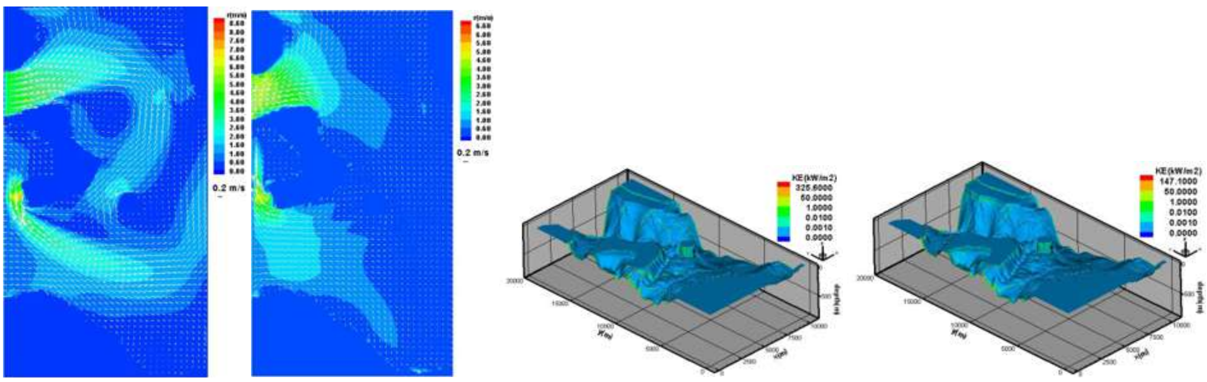
3.2. Numerical Simulation of Marine Currents in the Bunaken Strait

The current velocity is a key factor in the design of a marine current power plant, since it sets the limits for both the power output as well as the forces acting on the turbine and support structures [8]. Figure 4 shows simulated of velocity component distributions at seawater column when low (a) and high (b) tide currents. Generally, when low tide currents which water enters from left side section and then flows go to section of right side. A small part to top side section which previous rotate form two eddies like elliptic diameter at centre. The average velocity at enter of Bunaken strait is 1.46 m/s (figure 4a). On the contrary, when high tide current (figure 4b), current enters from right side section go to section of left side and a small part to top side section which previous happened eddy is very small at center east area near Bunaken island. The average velocity at enter of Bunaken strait is 0.85 m/s.



(a) (b) (c) (d)

Figure 4. Simulated of velocity component (2D) and kinetic energy (3D) distributions at seawater column when the tide currents of low (a and c) and high (b and d) at discharge of 1 Sv.



(a) (b) (c) (d)

Figure 5. Simulated of velocity component (2D) and kinetic energy (3D) distributions at seawater column when the tide currents of low (a and c) and high (b and d) at discharge of 2 Sv.

Simulated (2D) of velocity component distributions at seawater column when low (a) and high (b) tide currents shown Figure 5. Water flows when tide currents but the average velocities are different. When low tide current and high tide current at enter of Bunaken strait are 2.6 m/s and 2.0 m/s respectively.

The distributions of the kinetic energy when the tide currents of low (c) and high (d) in the Bunaken strait at discharge of 1 and 2 Sv respectively showed in figure 4 and figure 5. Discharge influence to the kinetic energy is very big where ever greater of discharge then ever greater also kinetic energy. Discharge of 1 Sv shows that there are about 0.05-2.54 kW/m^2 (when low tide currents) and 0.01-0.38 kW/m^2 (when high tide currents) kinetic energies, whereas at discharge of 2 Sv, 0.41-17.40 kW/m^2 (when low tide currents) and 0.11-2.77 kW/m^2 (when high tide currents) available in the Bunaken strait.

We can see generally that the values of current velocities and kinetic energy are bigger when low tide currents. That's because the cross sectional area of water that entered the Bunaken strait is smaller when low tide currents than when high tide currents.

4. Conclusions

Numerical simulation of marine currents in the Bunaken strait, North Sulawesi, Indonesia has presented. The values of the kinetic energy obtained by calculations could be enabling to choose a suitable place for installing the turbines adapted well for a future undersea electricity power plant in the Bunaken strait. The numerical results have shown that the values of current velocities and kinetic energy are bigger when low tide currents. At the discharge of 1 Sv, the average current velocities are 1.46 m/s (when low tide currents) and 0.85 m/s (when high tide currents), the distributions of the kinetic energy are 0.05-2.54 kW/m^2 (when low tide currents) and 0.01-0.38 kW/m^2 (when high tide currents). Whereas at discharge of 2 Sv, the average current velocities are 2.6 m/s (when low tide currents) and 2.00 m/s (when high tide currents), the distributions of the kinetic energy are 0.41-17.40 kW/m^2 (when low tide currents) and 0.11-2.77 kW/m^2 (when high tide currents). These results can used in the design of turbines for power generation marine currents in the Bunaken strait at depths below 60 meters.

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