A numerical study of Hydro-Hydraulic energy on Undular Tidal Bore phenomenon

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Abstract. A preliminary study of hydro-hydraulic energy on undular bores may support the invention of various kinds of technology related to renewable energy sourced from the potential of natural resources of Indonesia. Energy could be generated from one type of hydraulic jump that occurs in the river channel, namely undular tidal bore. The tidal bore phenomenon also exists in Indonesia, which occurs in the Kampar River, Riau, known as Bono. A numerical study of energy on wave-like tidal bore has been done for one type of bores, namely undular bores. The simulation of undular bores has been generated using the Computational Fluid Dynamics (CFD) approach assisted by the open-source CFD software, OpenFOAM which applied a turbulent model, namely one-equation Large Eddy Simulation (LES). The undular bores simulation in this study has been validated using experimental and numerical data from selected scientific references. Six simulations of undular bores have been performed based on six different values of Froude number, Fr = 1.04, 1.13, 1.20, 1.27, 1.34, and 1.41. Furthermore, the free surface of undular bores simulation was analyzed by emphasizing on the depth of upstream and downstream flows (d₁ and d₂ respectively). The rate of change of flow depth (∂d/∂x), energy dissipation (∆E), the rate of energy dissipation (∆E/∆x), and hydraulic power dissipated of undular bores (PUB) will increase as a function of the Froude number.

1. Introduction
In an open channel, such as a river, the transition from fast to slow flow is called a hydraulic jump. This flow transition occurs suddenly which is indicated by the rapid rise of the free surface in the flow. The difference between the two free surfaces will trigger the emergence of potential energy and the kinetic energy generated from the channel's flow velocity. In nature, this hydraulic jump mechanism is represented by a phenomenon known as a tidal bore. In the tidal bore, the volume of water from the estuary will move in the river canal to the upstream due to a tidal event in the estuary. This water flow moves by forming tsunami-like waves that can propagate up to 126 km from the estuary to the upstream like in the Garonne River, France [1]. The tidal bore has two flows that are opposite each other, namely upstream flow (normal flow) and downstream flow (tidal bore flow) [2]. These two flows collide that triggers the increasing in the free surface of the tidal bore flow. The tidal bore may only be generated by river channels that have characteristics such as shallow, gently sloping and narrowing at the river mouth [3]. In Indonesia, the tidal bore phenomenon occurs in the Kampar River,
Riau, which is known locally as Bono which has been used for surfing tourism and research [4]. Qualitatively, the energy generated by the Bono wave has a high magnitude which can be observed from its strength in eroding the banks of a river canal.

In this paper, a numerical study of the hydro-hydraulic energy generated by undular bores has been carried out. Undular bores flow simulations have been built using the open-source CFD software, OpenFOAM by applying the one-equation LES turbulent model. The flow simulation of the undular tidal bore has been validated with experimental and numerical data based on scientific references published by Chanson, (2010) [5] and Berchet, et al., (2018) [6]. After the simulation was validated, we then rebuilt the undular bores simulation by varying the Froude numbers, namely $Fr = 1.04, 1.13, 1.20, 1.27, 1.34$, and $1.41$. The six undular bores simulations are then analyzed to determine how much hydraulic power dissipated is generated by the undular bores as a function of Froude number.

2. Method

The simulation of the undular bores flow in this paper was built in 2D using the open-source CFD software, OpenFOAM. Open Source Field Operation And Manipulation (OpenFOAM) is an open source CFD software released and developed primarily by OpenCFD Ltd since 2004 [7]. This software applies the Finite Volume discretization and free surface capturing technique based on the Volume of Fluid (VoF) method to solve the Navier–Stokes equations [8]. The study of the hydro-hydraulic energy on the undular tidal bore phenomenon has followed the process described in Figure 1a. For the validation study, a simulation of undular bores has been generated based on the experimental setup proposed by Chanson [5]. Furthermore, the numerical parameters used in the validation study were applied to construct six simulations of undular bores with variations of the Froude number, $Fr$. The final step is to calculate the rate of change in depth of bores flow $\left(\frac{dz}{dt}\right)$, the energy dissipation of bores $\left(\Delta E\right)$, the rate of energy dissipation $\left(\frac{\Delta E}{E_1}\right)$, and the hydro-hydraulic power dissipated of undular bores $\left(P_{UB}\right)$.

![Flowchart of hydro-hydraulic energy study on undular tidal bore phenomenon: (a) general process, (b) generating of the numerical simulation.](image)

Figure 1. Flowchart of hydro-hydraulic energy study on undular tidal bore phenomenon: (a) general process, (b) generating of the numerical simulation.
The numerical simulation of the undular bores was generated by following the steps shown in Figure 1b. We have used the turbulent one-equation LES model available in OpenFOAM to solve the turbulence problem at the bottom of the flow. Some of the physical parameters applied in this numerical simulation are the kinematic viscosity of water and air that equal to \( \nu_{\text{water}} = 10^{-6} \text{ m}^2/\text{s} \) and \( \nu_{\text{air}} = 1.6 \times 10^{-5} \text{ m}^2/\text{s} \), respectively. The densities of water and air are set to \( \rho_{\text{water}} = 1000 \text{ kg/m}^3 \) and \( \rho_{\text{air}} = 1.2 \text{ kg/m}^3 \), respectively under a gravity acceleration that equal to \( g = 9.8 \text{ m/s}^2 \). A constant of turbulent kinetic energy \( k = 0.001 \text{ m}^2/\text{s}^2 \) has been applied in this simulation. In this paper, 2D numerical simulations of undular bores have been calculated using OpenFOAM CFD software version 8.0 in an Intel Core i7-860, CPU 3.0 GHz with 16 Gb RAM and 3 Gb DDR. The simulations built on Linux-based Operating System: Ubuntu 20.04 LTS. An open source application, Paraview 5.1.2 has been used to analyze and visualize the results of OpenFOAM calculations. Meanwhile, to display data in graphical form, a free interactive graphics program based on the command-line interface (CLI) has been used, namely Gnuplot 5.0.

In our simulation, the computational domain was divided into two blocks. Block 1 is the water zone where bore flow occurs. Block 2 is the air zone, which is free of water. We have made block 1 tighter than block 2 because our observation only emphasizes the flow of bores, not the air above it. This choice will certainly make the calculations carried out by the computer lighter. To make a reliable simulation, we have also made a simulation with the same configuration as Berchet et al., (2018) [6], by dividing the computational domain by the number of cell \( Cn = Cn_x \times Cn_y = 5000 \times 500 \). Furthermore, the time step of numerical simulations \( \delta t \) was set in a dictionary file, named controlDict, located in the System directory of OpenFOAM. To achieve temporal accuracy and numerical stability, the time step \( \delta t \) must be limited by the Courant-Friedrichs-Lewy (CFL) condition expressed as [2]:

\[
\delta t_{\text{CFL}} = \min \left( \frac{\delta x}{U}, \frac{\delta x^2}{\nu_{\text{w}}} \right) \tag{1}
\]

where \( \delta x, U, \) and \( \nu_{\text{w}} \) are the cell sizes in the x-axis direction, the magnitude of the water flow velocity, and the kinematic viscosity of the water by very small values, respectively. In our simulation, the time step has been set equal to \( \delta t = 0.001 \text{ s} \).

### 2.1. Flow Model

The flow model in OpenFOAM applies the continuity and momentum equations as expressed in Eqn. (2) and (3) below:

\[
\nabla \cdot \mathbf{u} = 0, \tag{2}
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \mathbf{f}(x, y, z, t). \tag{3}
\]

If a stress tensor, \( \tau_{ij} \), is applied, then Eqn. (2) and (3) could be written as follows:

\[
\frac{\partial u_i}{\partial x_j} = 0 \tag{4}
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + f_{\sigma_i}, \tag{5}
\]

where \( u, \rho, g, p \) and \( f_{\sigma_i} \) are velocity (m/s), density (kg/m\(^3\)), gravity acceleration (m/s\(^2\)), pressure (Pa), and the surface tension force (N/m) of fluid respectively. Stress tensor, \( \tau_{ij} \), depends linearly on the rate-of-strain tensor, \( S_{ij} \), expressed as:

\[
\tau_{ij} = -p \delta_{ij} + 2\mu S_{ij}, \tag{6}
\]

and

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \tag{7}
\]
Stress tensor $\tau_{ij}$ in Eqn. (6) is proportional to the rates of deformation associated with turbulent flow in a fluid. This form has resulted in a lot of turbulent modeling, one of which is the one-equation LES turbulent model used in our simulation.

### 2.2. Surface Tension Force

The water column in the open channel is generated by applying the Volume of Fluid (VoF) method introduced by Hirt and Nichols (1981) [8]. This method uses a volume fraction (written in OpenFOAM as $\alpha$) to define water-filled and non-water-filled cells in the computational domain. $\alpha$, a function of position and time, is expressed as:

$$
\alpha (x, y, z, t) = \begin{cases} 
1 & \text{position (x, y, z) filled water at time } t \\
0 < \alpha (x, y, z, t) < 1 & \text{position (x, y, z) interface at time } t \\
0 & \text{position (x, y, z) filled air at time } t.
\end{cases}
$$

The surface tension force, $f_{\sigma_i}$, in Eqn. (5) is determined as a continuum surface force (CSF) as follows:

$$
f_{\sigma_i} = \sigma \kappa \frac{\partial \alpha}{\partial x_i}
$$

with $\sigma$ is the surface tension constant and $\kappa$ is the curvature. For the multiphase case (water and air), equation (5) will involve a form of surface tension, $f_{\sigma_i}$ as in Eqn. (10). Thus, Eqn. (5) could be written as:

$$
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{1}{ho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} + \sigma \kappa \frac{\partial \alpha}{\partial x_i}
$$

Furthermore, Eqn. (4) and (10) could be solved by using the Finite Volume Method through programs that already exist in OpenFOAM. Initial condition for the water phase fraction, in which 1 for the water phase and 0 for the air phase could be specified in a `setFieldsDict` file, located in the `system` directory. This could be done by typing the command: `setFields` in Ubuntu terminal.

### 2.3. Froude Number

The original definition of Froude number, $Fr$ is a dimensionless number that is proportional to the square root of the ratio of the inertial force over the weight of the fluid, which could be written as [9]:

$$
Fr = \sqrt{\frac{\rho V^2 A}{\rho g d}} = \sqrt{\frac{\text{inertial force}}{\text{weight}}}
$$

where $\rho$, $g$, $V$, $A$, and $d$ are the fluid density (kg/m$^3$), the gravity acceleration (m/s$^2$), the mean flow velocity (m/s), the cross-sectional area (m$^2$), and flow depth (m), respectively. For a rectangular channel, the Froude number is defined as:

$$
Fr = \frac{V}{\sqrt{gd}}
$$

For the tidal bores, where the flow velocities of river and tidal bore have opposite directions, the definition of Froude number could be written as:

$$
Fr = \frac{V_0 + V_b}{\sqrt{gd_0}}
$$

with $V_0$, $V_b$, and $d_0$ are the initial velocity (equal to velocity of river), the bore velocity positive upstream, and initial water depth (equal to depth of river). Putra, et al., have classified the types of bores based on the Froude number, with Froude number $1 < Fr < 1.43$ is undular bores, $1.43 < Fr < 1.57$ is partially breaking bores, and $Fr > 1.57$ is totally breaking bores [2].
2.4. Hydro-Hydraulic Energy of Bores

The rapid increase in water depth in the event of tidal bores will trigger the rate of change in flow depth. The rate of change in depth of the bores flow for a smooth horizontal rectangular channel expressed in a Bélanger equation which can be written as [10]:

\[ \frac{d_2}{d_o} = \frac{1}{2} \times \left( \sqrt{1 + 8 \times Fr^2} - 1 \right) \]  

where \( d_o, d_2 \) dan \( Fr \) are water depth of river, water depth of tidal bore, and Froude number for tidal bore case in Eqn. (13), respectively. Applying the energy principle to the bores flow case provides an expression of the energy dissipation which is expressed as:

\[ \Delta E = \left( d_2 + \frac{(V_2 + V_b)^2}{2 \times g} \right) - \left( d_o + \frac{(V_0 + V_b)^2}{2 \times g} \right) \]  

with \( V_2 \) is the bore velocity negative downstream (m/s). For a smooth horizontal rectangular channel, the rate of energy dissipation could be written as:

\[ \frac{\Delta E}{E_i} = \frac{(\sqrt{1 + 8 \times Fr^2} - 3)}{16 \times (\sqrt{1 + 8 \times Fr^2} - 1) \times (1 + \frac{1}{2} \times Fr^2)} \]  

And finally, the hydro-hydraulic power dissipated of undular bores \( P_{UB} \) could be determined by the following equation:

\[ P_{UB} = \rho \times g \times (V_0 + V_b) \times d_o \times L_B \times \Delta E \]  

with \( L_B \) and \( P_{UB} \) are the transverse length of the bore roller (m), and the hydro-hydraulic power dissipated of undular bores (Watt), respectively.

3. Result and Discussion

3.1. Validation Study

Before building many simulations of undular bores based on variations of the Froude number, a validation step was carried out based on the experimental and numerical result in [5] and [6]. For the purposes of this validation, a simulation of undular bores has been constructed based on case A in [6], which applies the initial depth of water, \( d_0 = 0.165 \) m and the initial flow velocity, \( V_0 = -0.23 \) m/s.

Figure 2 shows an undular bores flow with \( Fr = 1.13 \) at \( t = 1.23 \) s and \( t = 7.03 \) s. In Figure 2, the initial flow starts moving from right to left and hits the left wall which is followed by the appearance of a new flow in the opposite direction. This new flow moves against the initial flow \( (V_0) \) with increasing flow depth \( (d_2) \) and then a series of waves with a certain velocity called the bore velocity \( (V_b) \) is formed.

To test the reliability of the simulations, the time evolution of the free surface of undular bores has been observed at \( x = 5.15 \) m and \( x = 7.15 \) m which also carried out in [6]. Figure 3a is a graph of the dimensionless time evolution of free surface of undular bores at the two observation locations compared with experimental and numerical data in [5] and [6]. Based on Figure 3a, the time evolution of the free surface \( (d/d_0) \) of undular bores produced by OpenFOAM has a good agreement with experimental measurements and numerical data. Furthermore, a comparative graph for the time evolution of horizontal and vertical components of the flow velocity, \( u/V_0 \) and \( u/V_b \), at \( x = 7.15 \) m
and \( y = 0.06 \) m has also been drawn as shown in Figure 3b. From the comparison graph, it shows that the results of calculation with OpenFOAM are similar to the results from experimental and numerical data. Therefore, from this validation study, it may be concluded that the undular bores simulation could be built using OpenFOAM which applies the one-equation LES turbulent model.

**Figure 2.** Velocity contour of undular bores flow in x direction at: (a) \( t = 1.23 \) s, and (b) \( t = 7.03 \) s.

**Figure 3.** Comparison graphics between experimental and numerical data in [5] and [6]: (a) time evolution of the free surface \( (d/d_0) \) of undular bores, (b) time evolution of horizontal and vertical components of the flow velocity \( (u/V_1) \) and \( (u_y/V_1) \), at \( x = 7.15 \) m and \( y = 0.06 \) m.

### 3.2. Hydro-hydraulic power of undular bores

Six variations of the Froude number have been calculated based on six simulations that apply initial flow velocity \( (V_0) \) and initial water depth \( (d_0) \) as shown in Table 1 (column 1 and 2). The free surfaces have been observed in the computational domain at \( x = 5.15 \) m and \( x = 7.15 \) m. Likewise, observations of the flow velocity have been done at point \( (x,y) = (7.15, 0.06) \) m in the computational domain (see Fig. 2). The study of hydro-hydraulic power of undular bores emphasizes on the observation of the depth of bores flow, the depth of bores flow \( (d_2) \), the bores velocity negative downstream \( (V_b) \), the bores velocity positive upstream \( (V_b) \), and the transverse length of the bore roller \( (L_b) \) which has been obtained as in Table 1.

Based on the observation data of undular bores simulation in Table 1, we have calculated the rate of change in depth of bores flow \( \left(\frac{\Delta d}{d_0}\right) \), the energy dissipation of bores \( \Delta E \), the rate of energy dissipation \( \left(\frac{\Delta E}{L_b}\right) \), and the hydro-hydraulic power dissipated of undular bores \( (P_{UB}) \) as shown in Table 2. We have correlated the four parameters of hydro-hydraulic power on undular bores simulation with the variation of the Froude number \( Fr \) as shown in Figure 4.
Table 1. Initial parameters and observation results on undular bores simulation.

| $d_0$ (m) | $V_0$ (m/s) | $Fr$ | $d_2$ (m) | $V_2$ (m/s) | $V_b$ (m/s) | $L_B$ (m) |
|-----------|-------------|------|-----------|-------------|-------------|-----------|
| 0.165     | -0.13       | 1.04 | 0.181     | -0.01       | 1.21        | 1.20      |
| 0.165     | -0.23       | 1.13 | 0.199     | -0.02       | 1.21        | 1.19      |
| 0.165     | -0.33       | 1.20 | 0.211     | -0.03       | 1.19        | 1.15      |
| 0.165     | -0.43       | 1.27 | 0.226     | -0.05       | 1.18        | 1.10      |
| 0.165     | -0.53       | 1.34 | 0.236     | -0.07       | 1.17        | 1.08      |
| 0.165     | -0.63       | 1.41 | 0.255     | -0.08       | 1.16        | 1.01      |

Table 2. Calculation results for four parameters of hydro-hydraulic power on undular bores simulation.

| $Fr$ | $\frac{d_2}{d_0}$ | $\Delta E$ | $\frac{\Delta E}{E_i}$ | $P_{UB_{max}}$ (Watt) |
|------|-------------------|-------------|--------------------------|-----------------------|
| 1.04 | 1.05              | 0.03        | 0.00002                  | 77.89                 |
| 1.13 | 1.17              | 0.06        | 0.00069                  | 157.63                |
| 1.20 | 1.27              | 0.08        | 0.0022                   | 217.08                |
| 1.27 | 1.36              | 0.09        | 0.0049                   | 279.07                |
| 1.34 | 1.46              | 0.11        | 0.0088                   | 332.02                |
| 1.41 | 1.56              | 0.14        | 0.0138                   | 395.18                |

Figure 4. A relationship of Froude number $Fr$ with: (a) the rate of change in depth of bores flow ($\frac{d_2}{d_0}$), (b) the rate of energy dissipation ($\frac{\Delta E}{E_i}$), (c) the energy dissipation of bores ($\Delta E$), and (d) and the hydro-hydraulic power dissipated of undular bores ($P_{UB_{max}}$).

We have obtained the relationships that shows that increasing the value of $Fr$ will lead to an increase in the depth of bores, energy dissipation, and the rate of energy dissipation as shown in Figure 4. This increase is affected by the initial flow velocity which is a function of $Fr$. The high initial
velocity will suppress the bore flow in the opposite direction to this initial flow. The studies in [5], [6], and [9] have confirmed that this initial flow velocity will affect the increase in the depth of bores and the energy generated. In nature, this initial flow rate can be associated with the river upstream flow. This river flow will hit the flow of the tidal bore which moves upstream due to a tidal event in the estuary.

Furthermore, we have calculated the maximum hydro-hydraulic power $P_{UB_{max}}$ for each simulation with various $Fr$ as shown in Figure 4d. We have found that a maximum value of $P_{UB_{max}}$ is 395.18 Watt which occurs in the bores with $Fr = 1.41$. The maximum power was generated when the change in bores depth is ~ 0.1 m with an initial velocity of ~ 0.63 m/s. While the minimum power in this simulation occurs at bores with $Fr = 1.04$, which equal to 77.89 Watts. This value is obtained when the change in depth of bores is ~ 0.02 m with an initial velocity of ~ 0.13 m/s. The change in depth of bores is associated with $Fr$ which has been expressed in a relationship shown in Figure 4a.

### 4. Conclusion

A preliminary study of the hydro-hydraulic energy of undular bores was carried out based on variations of Froude number $Fr$. The simulations of the undular bores flow as a function of $Fr$ have been built using the open-source CFD software, OpenFOAM by applying the one-equation LES turbulent model. Flow validation has been performed by comparing the time evolution of the free surface, horizontal and vertical components of the flow velocity of undular bores with experimental and numerical data from selected scientific references. The comparative graph have shown that our simulation have a good agreement with experimental measurement and numerical data. Furthermore, the energy relationships of the undular bores and Froude number have been obtained based on the numerical observations made. The rate of change in depth of bores flow ($\frac{\Delta h}{\Delta t}$), the energy dissipation of bores ($\Delta E$), the rate of energy dissipation ($\frac{\Delta E}{E_t}$), and the hydro-hydraulic power dissipated. of undular bores ($P_{UB}$) will increase as the Froude number increases. For the future, the experimental observations need to be made to verify the calculation of the hydraulic power dissipated of undular bores that have been carried out in this paper.

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### References

[1] Bonneton P, Filippini A G, Arpaia L, Bonneton N and Ricchiuto M 2016 Conditions for tidal bore formation in convergent alluvial estuaries *Estu. Coast. Shelf Sci.* 172 121–127 doi: 10.1016/j.ecss.2016.01.019

[2] Putra Y S, Beaudoin A, Rousseaux G, Thomas L and Huberson S 2019 2D numerical contributions for the study of non-cohesive sediment transport beneath tidal bores *Comptes Rendus - Mec.* 347(2) 166–180 doi: 10.1016/j.crme.2018.11.004

[3] Bonneton P et al. 2011 On the occurrence of tidal bores - The Garonne River case *J. Coast. Res.* 64 1462–1466

[4] Putra A, Wisja U J and Kusumah G 2017 Spatial Analysis of the River Line and Land Cover Changes in the Kampar River Estuary: The Influence of the Bono Tidal Bore Phenomenon *Forum Geogr.* 31(2) 220–231

[5] Chanson H 2010 Undular tidal bores: Basic theory and free-surface characteristics *J. Hydraul. Eng.,* 136(11) 940–944 doi: 10.1061/(ASCE)HY.1943-7900.0000264

[6] Berchet A, Simon B, Beaudoin A, Lubin P, Rousseaux G and Huberson S 2018 Flow fields and particle trajectories beneath a tidal bore: A numerical study *Int. J. Sediment Res.* 33(3) 351–370 doi: 10.1016/j.ijscr.2018.03.001
[7] OpenCFD 2020 About OpenFOAM https://www.openfoam.com/ (accessed Oct. 12, 2020)
[8] Hirt C and Nichols B 1981 Volume of fluid (VOF) method for the dynamics of free boundaries
   J. Comput. Phys. 39 201–225
[9] Chanson H 2004 The Hydraulics of Open Channel Flow: An Introduction, Second Edi.
   (Burlington,: Elsevier Butterworth-Heinemann)
[10] Lubin P and Chanson H 2017 Are breaking waves, bores, surges and jumps the same flow?,
    Environ. Fluid Mech. 17(1) 47–77 doi: 10.1007/s10652-016-9475-y