A numerical study of tidal bores

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Abstract. A tidal bore is a natural phenomenon forming a positive surge upstream and it has a remarkable effect on estuary zones and river ecologies. The tidal bore formation controlled by channel properties, tidal characteristics, and river discharge remains a research challenge. In this study, a tidal bore formation and its hydrodynamics characteristics have been numerically investigated by using a two-dimensional version of OpenFOAM (Open Source Field Operation and Manipulation) model to obtain a better understanding of the effects of flow velocity before arrival of the bore ($V_1$), initial water depth ($d_1$), and Froude number ($Fr$) on the propagation of the tidal bore. The numerical simulation results have confirmed earlier findings obtained under both field and laboratory data in which types of the tidal bores depend on the Froude number. An undular tidal bore occurs when $1 \leq Fr < 1.25$, while partially breaking undular bore appears for $1.25 \leq Fr < 1.5 - 1.6$. Further simulation results have revealed that the flow velocity before the bore passage (downstream flow or $V_1$) is more dominant than the initial water depth in affecting the Froude number. Meanwhile, the bore celerity ($U_b$) is more affected by the initial water depth compared to the flow velocity before the bore arrival. It is found that the Froude number does not directly affect wave parameters of the bore, such as amplitude, length, period, and steepness of the wave. However, the wave length and period are directly proportional to the initial water depth, whereas the wave amplitude and steepness are associated with the velocity prior to the bore passage.

1. Introduction

A tidal bore is a phenomenon in which the leading edge of the incoming tide forms a series of waves that propagate upstream in a narrowing channel mouth against the direction of the river current during the early flood tide under spring tide conditions with the tidal range exceeds 4 to 6 m [1]. Tidal bores induce strong turbulent mixing and have a remarkable effect on estuary and river ecosystems, which are known as feeding and spawning grounds for various species [2]. For examples, the pororoca tidal bore on the Amazon River (Brazil) sets organic matters into suspension and its estuarine zone is the feeding grounds of piranhas. In France, several birds of prey are fishing behind the tidal bore front and next to the banks. In Australia, crocodiles feed behind the bore. Therefore, the tidal bores have a significant impact on the ecosystems [3].

It is estimated worldwide that over 400 estuaries are affected by tidal bores [4]. In several estuaries, the tidal bores have become a major tourism attraction and a number of local communities organize some festivals around the tidal bores [3], for example: local and cultural history on the tidal bore
('mascaret') of the Seine River and the Dordogne and Severn Rivers as the sites of well-known tidal bore surfing competitions. In addition, the tidal bore of the Turnagain Inlet in Alaska is a feature of many organized tours, and its schedules are well-advertised. The Chinese Moon festival along the Qiantang River can attract more than 300,000 people each year. In the case of Indonesia, there is a tidal bore wave, which is locally known as Bono or Seven Ghosts, in Kampar River located on the east side of Sumatra. The Bono is one of the ten best river surfing waves in the world and becomes an amusing local attraction for residents and visitors. In general, tidal bores, which provide opportunity for recreational inland surfing, have an impact on a range of socioeconomic resources. Hence, preservation of the existence of a tidal bore as a natural phenomenon and as a potential asset is important and necessary.

A tidal bore is a very fragile process. The bore development is based upon a delicate balance between the tidal range, the freshwater river (downstream) flow conditions, and the river morphology. Once formed, the bore existence relies upon the exact momentum balance between the initial and new flow conditions. Based on theoretical considerations, it has been shown that this balance may be easily disturbed by some changes in the boundary conditions and freshwater runoff [3]. A number of tidal bores disappeared because of man-made interventions such as river training, dredging, and damming. For example, the tidal bore of the Seine River (France) does not longer exist after extensive training works and dredging; the Colorado River bore (Mexico) drastically shrinks after some dredging as well as the damming of the river. The tidal bore of the Petitchodiac River (Canada) almost disappeared after construction of an upstream barrage [3]. Moreover, many tropical coastal regions are considered to be at great risk because of strong economic and population growth paired with limited environmental management. For example, land-use changes of the tropical catchment area of the Kampar River (Indonesia), including rubber and oil palm plantation, lead to increased soil erosion and sedimentation. These conditions may threat the existence of the Bono tidal bore of the Kampar River.

Tidal bores are most often in the form of undular bores characterized by a train of well-formed free-surface undulations. These have been extensively studied in laboratory experiments [4-6], analytical models [e.g., 7, 8], field observation [e.g., 9], and numerical simulations [10-13], revealing nonlinear interactions over a range of spatiotemporal scales. However, due to complexity of the tidal bore driving mechanism and its characteristics (e.g., generation, propagation, and mutual interactions among the bore, river discharges, and bathymetry), a better understanding of the tidal bore formation and its prediction remains a great challenge to study. It is important to obtain a better understanding of the main driving mechanism of a tidal bore and its characteristics both for scientific and practical reasons.

According to [5], there are three types of tidal bore classified by the Froude number \( Fr = (U_b + V_f)/\sqrt{gd_1} \): (1) undular tidal bore for \( 1 \leq Fr < 1.25 \); (2) partially breaking undular bore for \( 1.25 \leq Fr < 1.5 - 1.6 \); and (3) breaking bore for \( Fr \geq 1.6 \). In addition, the tidal bore does not exist for a flow with \( Fr < 1 \) [5]. In the present study, conditions for tidal bore formation and its hydrodynamic characteristics have been studied numerically using a two-dimensional (2D) version of OpenFOAM (Open Source Field Operation and Manipulation) model. First, the numerical simulations were carried out to reproduce experimental study of [5] and numerical study of [14] for model verification. Furthermore, characterization of the effect of Froude number, flow velocity before bore arrival (downstream flow or river discharges), and initial water depth on the generation and propagation of tidal bores were investigated in further detail.

2. Material and method

2.1. Model Description

The simplified version of the channel developed by [5] and [14] was employed in this study to verify the present simulated results (Figure 1). Domain of the numerical model is a rectangular-shaped canal with 10 m length and 0.5 m height. Horizontal and vertical grid resolutions of the model domain are 10 mm and 1 mm, respectively. Flow velocity before arrival of the bore or downstream flow \( (V_1) \) with initial water depth \( (d_1) \) was imposed as a generating force in the simulation.
In this model, tidal bores propagating upstream were generated after the impact of a downstream flow ($V_1$) against a closing gate (wall) on left side of the canal (Figure 1). On down right side of the canal, there is an inlet where boundary conditions for a phase fraction parameter ($\alpha$) and horizontal flow velocity ($u_x$) are set to constant values, namely $\alpha = 1$ (the grids at the inlet boundary is contained entirely by water) and $u_x = V_1$. Meanwhile, vertical velocity component ($u_z$) in the inlet is set to be 0 (no slip condition). Furthermore, on the left, upper right, and bottom (bed) sides of the canal’s wall, no slip and zero gradient boundary conditions are set for the flow velocity vector and the phase fraction parameter, respectively. In addition, zero gradient boundary conditions are set both for the flow velocity vector and the phase fraction parameter on upper side of the canal. The simulation was run until the upstream propagating tidal bore reached the right boundary of the canal’s wall. An automatic time-step adjustment facilitated by the OpenFOAM model was used in this simulation.

![Figure 1. Numerical model domain.](image)

2.2. Governing Equations

InterFOAM solver as one of many solvers contained in the OpenFOAM model (www.openfoam.org) was used in this study. In this model, it is assumed that the flow is incompressible, transient, turbulent, and multiphase with immiscible property between air and water. The model solves equations of continuity and momentum, as in Equation (1) and Equation (2), respectively, as follow:

\[
\nabla \vec{u} = 0
\]

\[
\frac{\partial \rho \vec{u}}{\partial t} + \nabla (\rho \vec{u} \vec{u}) = -\nabla p + \nu \nabla^2 \vec{u} - \nabla \cdot \tau_{SGS}
\]

where $\vec{u}$ is flow velocity vector, $\rho$ is density, $p$ is pressure, $\nu$ is kinematic viscosity, and $t$ is time. The last two terms on the right side of the momentum equation represents the diffusion effects or the turbulent mixing of fluid motion. In this model, the diffusion coefficient (kinematic viscosity; $\nu$) is estimated by a mixed scale (MS) model comprising the Smagorinsky model and the turbulent kinetic energy (TKE) model.

In this study, effect of air density on the water column grid is considered. It means that air may be contained inside a grid cell, which in turn changes the density value of the grid. This aspect is important since tidal bore is a phenomenon dealing with greatly fluctuating interface. In addition, in this study, a volume of fluid (VOF) method was used to model the interface fluctuations. It is performed by defining a phase fraction parameter ($\alpha$) in which its value ranging between 0 and 1. In a grid, if the value of $\alpha$ is 0, it means that the grid is contained entirely by air, and hence the air density value is used in the Equation (2). On the other hand, the grid is contained entirely by water if the phase fraction parameter $\alpha$ is 1, and as a consequence the water density value is used in the Equation (2). For neither of both phase fraction values, the density value used in the Equation (2) is calculated using Equation (3), as follow:

\[
\text{Air} \quad \text{Water} \quad \text{Downstream} \quad \text{Upstream}
\]

\[
\text{Air} \quad \text{Water} \quad \text{Downstream} \quad \text{Upstream}
\]
\[ \rho = \alpha \rho_{\text{liquid}} + (1 - \alpha) \rho_{\text{gas}} \]  

(3)

where \( \rho \) is final density, \( \alpha \) is the phase fraction parameter, \( \rho_{\text{liquid}} \) is density of water, and \( \rho_{\text{gas}} \) is density of air. The value of phase fraction parameter \( \alpha \) is determined by the following transport equation (www.openfoam.org):

\[
\frac{\partial \alpha}{\partial t} + \nabla (\alpha \vec{u}) + \nabla (\alpha(1 - \alpha) \vec{u}_r) = 0
\]

(4)

where \( \vec{u}_r \) is a velocity field normal to the interface.

3. Results and discussion

In this section, we present two steps of our simulation results. The first step (henceforth referred to as OF1 simulation) aims to verify the present simulated results with those of [14] and experimental results of [5], while the second one (hereafter known as OF2 simulation) aims to investigate roles of the Froude number (\( Fr \)), the velocity prior to the bore passage (\( V_1 \)), and the initial water depth (\( d_1 \)) on the generation and propagation of tidal bores.

In the OF1 simulation, a simplified version of model domain of [14] was employed, as shown in Figure 1. As explained in Section 2.1, the horizontal and vertical grid resolutions used in the present study are 10 mm and 1 mm, respectively. The grid resolutions of the present model were coarser than those of [14] with grid spacing of about 2 mm (horizontal) and 1 mm (vertical). Downstream flow velocity before arrival of the bore (\( V_1 \)) with initial water depth (\( d_1 \)) was imposed for tidal bore generation. As in the simulation of [14], tidal bores propagating upstream (to the right) were generated after the impact of the downstream flow (\( V_1 \); to the left) against a closing gate (wall) on left side of the canal (indicated by red bar in the Figure 1). Initial data values used for the model verification (the OF1 simulation) are similar to those of [14], as shown in Table 1.

### Table 1. Initial data values used for model verification (the OF1 simulation).

| \( d_1 \) (m) | \( V_1 \) (m/s) |
|---------------|----------------|
| 0.199         | 0.189          |

For the OF2 simulation, there are 12 scenarios of model runs (Table 2), which can be categorized into three types, namely Type A with constant downstream flow velocity (\( V_1 \)) and varied initial water depth (\( d_1 \)), Type B with constant initial water depth and gradually varied downstream flow velocity, and Type C in which almost similar to the Type B except for rapidly varied downstream flow velocity. Each type of the OF2 simulation has its own purpose. The Types A, B, and C were performed to study the effects of initial flow depth (\( d_1 \)), flow velocity before bore passage (\( V_1 \)), and Froude number on the characteristics of tidal bore formation, respectively.

### Table 2. Initial data values used for the OF2 simulation.

| Number | Types | Scenarios | \( d_1 \) (m) | \( V_1 \) (m/s) | Percentage of the initial data values of the OF2 simulation (OF2_S) compared to the OF1 simulation (OF1_S) |
|--------|-------|-----------|---------------|----------------|------------------------------------------------------------------|
| 1.     | A1    | A1        | 0.099         | 0.189          | \( d_1 \) of the OF2_S = 50% \( d_1 \) of the OF1_S |
| 2.     | A2    | A2        | 0.149         | 0.189          | \( d_1 \) of the OF2_S = 75% \( d_1 \) of the OF1_S |
| 3.     | A3    | A3        | 0.249         | 0.189          | \( d_1 \) of the OF2_S = 125% \( d_1 \) of the OF1_S |
3.1. Model verification (the OF1 simulation)

The OF1 simulation results clearly showed the existence of undular tidal bores propagating upstream as the impact of a downstream flow against the wall on the left side of the canal (Figure 2). In the Figure 2, the propagation of undular bore is indicated by time evolution of free surface, which is represented by ratio profile of the water depth after the bore arrival \(d_2\) to the initial one \(d_1\). In the OF1 simulation, the simulated free surfaces were compared to those of [14] and experimental results of [5]. Comparison of the present simulated free surface for undular bores is in general agreement with those of [14] and of [5]. Compared to the simulation results of [14], the present simulated undular bores are generally closer to the physical model results of [5].

Table 3 shows detailed values of comparison of tidal bore parameters and characteristics (e.g., Froude number \(F_r\), bore celerity \(U_b\), water depth after the bore arrival \(d_2\), maximum water depth \(d_{max}\), minimum water depth \(d_{min}\), wave amplitude \(a_w\), wave length \(L_w\), and wave period \(T_w\)) among the present simulated results, those of [14], and the experimental results of [5]. Definition of the tidal bore wave
parameters and characteristics is shown in Figure 3. The general agreements between the present simulated results with those of [14] and with those of [5] were reasonably encouraging, with mean percentage difference of about 4% and 2.5%, respectively (Table 3). Meanwhile, the percentage difference between the results of [14] and those of [5] is 3.4%. Hence, the comparison of the present results to those of [5] is performing better although the grid cells used in the present model (10 x 1 mm\(^2\)) were coarser than those of [14] with grid resolution of about 2 x 1 mm\(^2\). The better performance of the present applied OpenFOAM model was probably caused by more accurate representation of numerical diffusion term implemented in the model in preventing errors due to the occurrence of numerical waves. The forcings for tidal bore generation and open boundary treatments implemented in the applied model are based on a large number of assumptions and approximations. Nevertheless, the OF1 simulation and experimental results of tidal bore parameters are generally in agreement. For further study and to improve the performance of the present study, it is suggested to use an adequate estimation of the bottom friction effect and more appropriate treatments along the boundaries.

![Figure 3. Definition of tidal bore wave parameters for undular bore (modified from [15]).](image)

### Table 3. The comparison of tidal bore parameters and characteristics for the OF1 simulation.

|                  | Fr  | \(U_b\) (m/s) | \(d_z\) (m) | \(d_{\text{max}}\) (m) | \(d_{\text{min}}\) (m) | \(a_w\) (m) | \(L_w\) (m) | \(T_w\) (s) | Mean Percentage Difference (%) |
|------------------|-----|---------------|-------------|-------------------------|-------------------------|-------------|-------------|------------|-------------------------------|
| Physical model [5] | 1.08 | 1.32          | 0.228       | 0.240                   | 0.218                   | 0.011       | 1.544       | 1.170      |                               |
| Numerical model [14] | 1.10 | 1.34          | 0.229       | 0.243                   | 0.217                   | 0.013       | 1.528       | 1.140      |                               |
| Present study    | 1.10 | 1.33          | 0.227       | 0.240                   | 0.219                   | 0.011       | 1.425       | 1.071      |                               |
| Percentage difference between the present results and those of [5], in % | 1.9  | 0.8           | 0.4         | 0.0                     | 0.5                     | 0.0         | 7.7         | 8.5        | 2.5                           |
| Percentage difference between the present results and those of [14], in % | 0.0  | 0.7           | 0.9         | 1.2                     | 0.9                     | 15.4        | 6.7         | 6.1        | 4.0                           |
| Percentage difference between the results of [14] and those of [5], in % | 1.9  | 1.5           | 0.4         | 1.3                     | 0.5                     | 18.2        | 1.0         | 2.6        | 3.4                           |

3.2. The OF2 simulation

The OF2 simulation was carried out to investigate the effects of initial flow depth (Type A), flow velocity before bore passage (Type B), and Froude number (Type C) on the characteristics of tidal bore formation. As shown in the Table 2, Scenarios A1-A4 were performed for the case of constant flow velocity prior to the bore passage (\(V_1 = 0.189\) m/s) and varied initial water depth (\(d_1\)), namely 50%, 75%, 125%, and 150 % the initial depth of the OF1 simulation, respectively. Meanwhile, Scenarios B1-B4 were carried out for the case of constant initial water depth (\(d_1 = 0.199\) m) and gradually varied \(V_1\) (50%, 75%, 125%, and 150 % flow velocity prior to the bore passage of the OF1 simulation, respectively). Furthermore, to investigate roles of the Froude number (\(Fr = (U_b + V_1)/\sqrt{gd_1}\)), Scenarios C1-C4 were conducted by setting rapidly varied \(V_1\) (10%, 200%, 400%, and 600 % of flow
velocity prior to the bore passage of the OF1 simulation, respectively) and constant initial water depth ($d_1 = 0.199$ m). A detailed description of the OF2 simulation results (Types A, B, and C) is described in the following sections.

3.2.1. Simulation of Type A (constant flow velocity before the bore passage and varied initial water depth)

Figure 4a shows undular bore propagation for the simulations of Type A and OF1 when the first bore crest reaches $x = 7.15$ m. In these simulations, it was found that the Froude number ($Fr$) ranged from 1.026 to 1.132 (Table 4). The simulated values of the Froude number $Fr$ meet the criteria for tidal bore formation, namely undular tidal bore taking place at $1 \leq Fr < 1.25$ \cite{5}. Variation of tidal bore parameters for those simulations is shown in the Table 4 and Figures 5a-5g. It was found that the Froude number $Fr$ tends to decrease with the increase in the initial water depth (Figure 5a and Table 4). This result is associated with definition of the Froude number ($Fr = (U_b + V_s) / \sqrt{gd_1}$) which depends inversely on the square root of the initial water depth ($d_1$). Change of the $Fr$ value for the simulation of Type A (from the Scenario A1 to the Scenario A4) is 9.28%. Furthermore, the effect of the initial water depth on other wave parameters of the bore can be clearly seen in Figures 5b-5g and Table 4. In this case, values of bore celerity $U_b$, wave length $L_w$, and wave period $T_w$ increase with increasing the initial water depth, whereas ratio of water depths after and before the bore passage ($d_2/d_1$), bore steepness ($a_w/L_w$), and bore wave amplitude ($a_w$) decrease with increase in initial water depth. In this case, change of the $U_b$ value from the Scenario A1 to the Scenario A4 is 69.44%.

| Table 4. Variation of tidal bore wave parameters and characteristics for the OF1 and OF2 simulations. |
|---|
| Scenarios | $d_1$ (m) | $V_s$ (m/s) | Type of tidal bore | $Fr$ | $U_b$ (m/s) | $d_2$ | $d_{max}$ | $d_{min}$ | $a_w$ | $L_w$ (m) | $T_w$ (s) | $a_w/L_w$ |
| OF1 | 0.199 | 0.189 | undular | 1.100 | 1.330 | 1.141 | 1.206 | 1.101 | 0.065 | 1.425 | 1.071 | 0.009 |
| A1 | 0.099 | 0.189 | undular | 1.132 | 0.926 | 1.202 | 1.293 | 1.131 | 0.091 | 0.750 | 0.810 | 0.015 |
| A2 | 0.149 | 0.189 | undular | 1.092 | 1.130 | 1.161 | 1.228 | 1.114 | 0.067 | 1.075 | 0.951 | 0.012 |
| A3 | 0.249 | 0.189 | undular | 1.026 | 1.413 | 1.124 | 1.177 | 1.088 | 0.052 | 1.700 | 1.203 | 0.008 |
| A4 | 0.299 | 0.189 | undular | 1.027 | 1.569 | 1.114 | 1.157 | 1.084 | 0.043 | 1.900 | 1.211 | 0.008 |
| B1 | 0.199 | 0.095 | undular | 1.009 | 1.314 | 1.070 | 1.095 | 1.050 | 0.025 | 1.500 | 1.115 | 0.003 |
| B2 | 0.199 | 0.142 | undular | 1.021 | 1.284 | 1.111 | 1.141 | 1.075 | 0.030 | 1.425 | 1.110 | 0.006 |
| B3 | 0.199 | 0.236 | undular | 1.088 | 1.284 | 1.176 | 1.251 | 1.121 | 0.075 | 1.375 | 1.046 | 0.014 |
| B4 | 0.199 | 0.284 | undular | 1.123 | 1.284 | 1.216 | 1.312 | 1.151 | 0.095 | 1.350 | 1.051 | 0.019 |
| C1 | 0.199 | 0.019 | - | 0.014 | - | - | - | - | - | - | - | - |
| C2 | 0.199 | 0.378 | undular | 1.190 | 1.284 | 1.286 | 1.508 | 1.136 | 0.221 | 1.300 | 1.012 | 0.034 |
| *C3 | 0.199 | 0.756 | partially breaking | 1.421 | 1.228 | 1.603 | 1.844 | 1.392 | 0.241 | 0.800 | 0.651 | 0.060 |
| **C4 | 0.199 | 1.134 | breaking | 1.753 | 1.314 | 1.940 | 2.266 | 1.794 | 0.327 | 0.700 | 0.533 | 0.093 |

Notes: observation was carried out at $x = 7.15$ m; *observation was carried out at $x = 1.5$ m; and **observation was carried out at $x = 0.65$ m.

3.2.2. Simulation of Type B (constant initial water depth and gradually varied flow velocity prior to the bore passage)

Undular bore propagation for the simulations of Type B and OF1 is shown in Figure 4b. Similar to the Type A simulation, the Figure 4b shows the bore propagation when the first bore crest arrives at $x = 7.15$ m. In the simulation of Type B, it was found that the Froude number ($Fr$) was varied in the range between 1.009 and 1.123 (Table 4), which meets the conditions for the tidal bore formation ($1 \leq Fr < 1.25$). Variation of tidal bore parameters for the Type B simulation is shown in the Table 4 and Figures 5h-5n. It was found that the Froude number $Fr$ tends to increase with the increasing the
flow velocity prior to the bore passage ($V_1$) (Figure 5h and Table 4). This result is associated with definition of the Froude number ($Fr = (U_b + V_1)/\sqrt{gd_1}$) which is directly proportional to the flow velocity before arrival of the bore ($V_1$). In this type simulation, change of the $Fr$ value from the Scenario B1 to the Scenario B4 is 11.30%. Further results have showed that the $V_1$ influences the ratio of water depths after and before the bore passage ($d_2/d_1$), bore steepness ($a_w/L_w$), and bore wave amplitude ($a_w$). Values of $d_2/d_1$, $a_w/L_w$, and $a_w$ increase with the increase in the downstream flow ($V_1$), as shown in Figures 5l-5n and Table 4. However, the $V_1$ does not directly affect the bore celerity $U_b$, wave length $L_w$, and wave period $T_w$. Change of the $U_b$ value for the simulation of Type B (from the Scenario B1 to the Scenario B4) is 2.28%.

![Figure 4. Undular bore propagation for the simulations of OF1 and OF2 when the first wave crest of tidal bore reaches $x = 7.15$ m: (a). Type A (A1-A4); (b). Type B (B1-B4); and (c). Type C (C1-C4). In each figure (a – c), the OF1 simulation results are also shown.](image-url)
Figure 5. (a) and (h) are Froude number ($Fr$) for the Scenarios A1-A4 and B1-B4, respectively; (b) – (g) and (i) – (n) are variation of tidal bore wave parameters for each scenario (A1-A4 and B1-B4), respectively. In each figure (a – n), the OF1 simulation results are also shown.
3.2.3. Simulation of Type C (constant initial water depth and rapidly varied flow velocity prior to the bore passage)

Simulation of Type C was carried out by setting rapidly varied $V_j$ to investigate roles of the Froude number ($Fr$) on tidal bore characteristics. In this simulation, it was found that the $Fr$ was rapidly varied in the range between 0.014 and 1.753 (Table 4). The simulation result has shown that undular tidal bore does not occur when $Fr = 0.014$ (Scenario C1 in Table 4 and Figure 4c) because it does not meet requirements for the tidal bore formation ($1 \leq Fr < 1.25$). Meanwhile, undular tidal bore exists in the simulation of Scenario C2 when $Fr = 1.190$ (Table 4 and Figure 4c). Further simulation results have revealed the existence of partially breaking undular and breaking tidal bores when the simulated Froude number values are $Fr = 1.421$ (Scenario C3) and $Fr = 1.753$ (Scenario C4), as shown in Figure 4c and Table 4. The present numerical results have confirmed earlier studies performed both in the field and the laboratory [e.g., 2, 4, 5, 6, and 9], namely types of the tidal bores depending upon the Froude number (undular tidal bore, $1 \leq Fr < 1.25$; partially breaking undular bore, $1.25 \leq Fr < 1.5 - 1.6$; and breaking bore, $Fr \geq 1.6$).

4. Conclusions

The present simulated results of tidal bore parameters have been verified with both numerical model results [14] and laboratory data [5]. In general, a reasonable agreement between the present simulated results with those of [14] and those of [5] exists, with mean percentage difference between the present results with both data comparison of about 4% and 2.5%, respectively. It was found that the Froude number tends to decrease (increase) with the increase in the initial water depth (the flow velocity prior to the bore passage) in which the downstream flow (11.30%) is more dominant than the initial water depth (9.28%) in affecting the Froude number. Meanwhile, the bore celerity is more affected by the initial water depth (69.44%) compared to the downstream flow (2.28%). Values of bore celerity, wave length, and wave period (bore steepness and wave amplitude) increase (decrease) with increasing the initial water depth. Further results have shown that the downstream flow affects the bore steepness and the wave amplitude in which they increase with the increase in the downstream flow. However, the downstream flow does not directly affect the bore celerity, wave length, and wave period. In addition, the present study results have confirmed previous studies conducted both in the field and the laboratory, namely the Froude number affecting types of the tidal bores (undular tidal bore, $1 \leq Fr < 1.25$; partially breaking undular bore, $1.25 \leq Fr < 1.5 - 1.6$; and breaking bore, $Fr \geq 1.6$).

In the current study, the OpenFOAM model has been implemented only in a simplified version of a channel. Nevertheless, a better understanding of the main driving mechanism of a tidal bore and its characteristics has been obtained through the present simulation results. These present results are a step toward a better understanding of tidal bores in real estuaries. For further study, application of the model can also be extended to predict the bore hydrodynamics in real estuaries and rivers. A greater understanding of the bore hydrodynamics could be significantly valuable for designing proper management plans of estuarine and river systems, such as determination of the proper sites for dredging and construction activities to guarantee the safety of water tourism and recreational infrastructure and navigation as well as to conserve the tidal bore phenomenon.

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