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APPLICATION OF FINITE DIFFERENCE METHOD IN SIMULATING 2D PARTIAL DAM-BREAK FLOW WITH AN OBSTACLE

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ABSTRACT

A numerical model capable of simulating the dam-break flow is required to reduce the detrimental impact on the downstream area of the dam. This study aims to see how the characteristics and patterns of flow due to partial dam failure and the presence of an obstacle in the floodplain. In real life, the obstacle can be considered as a building. In this research, a model based on the FTCS method was developed with the addition of a Hansen numerical filter. This model is known as the FTCS-Hansen model. The Hansen filter in this study is used to enhance the numerical of the model and reduce oscillations due to shock waves. The FTCS-Hansen model simulates a 2D partial dam break with an obstacle. The simulation results are compared with other simulation results from previous studies. This comparison intends to see the performance of the FTCS-Hansen model. The results show good agreement between the FTCS-Hansen model and other numerical models. In addition, the complicated dam-break flow characteristics due to the presence of an obstacle (reflection and diffraction) can also be well captured by the FTCS-Hansen model.

INTRODUCTION

Dam failure or dam break is a phenomenon where the dam collapses (partial or complete), which causes an uncontrolled flow of water. Dam break flow will give a lot of losses to the area downstream of the dam. These losses can be in the form of environmental damage, property damage, and loss of life, as described in Glotov et al. (2018), Latrubesse et al. (2020), Lumbroso et al. (2021), Silva Rotta et al. (2020). One way to minimize the negative impact of the flow due to dam failure is to study the characteristics of the flow. Mathematical modeling is a common way to examine the phenomenon of flooding due to dam failure and its effect on a building in downstream areas. The advantage of the mathematical model is its effectiveness, especially cost.

Mathematically, modeling of the dam-break flow is generally carried out based on shallow-water equations (SWEs), as in Hafiyyan et al. (2021), Hafiyyan et al. (2021), Maitsa et al. (2020). These equations can be solved using numerical techniques, for instance, the finite-difference method or FDM (D. Liang et al., 2007; Magdalena & Eka Pebriansyah, 2022; Ouyang et al., 2013; Xing & Shu, 2005), the finite-element method or FEM (Lee, 2014; S. J. Liang & Hsu, 2009; Seyedashraf & Akhtari, 2017; Zhao et al., 2014), and the finite-volume method or FVM (Huang et al., 2013; Lakhlifi et al., 2018; Magdalena et al., 2021). In present study, the finite difference method (FDM) is used to solve the SWEs and simulate 2D dam-break problem. The advantage of this method is its simplicity (Peng, 2012). Yet, finite difference methods of dealing with shock waves tend to be unstable. Thus, special treatment is needed to deal with this problem.

FDM is a numerical method that is commonly used in solving differential equations, both ordinary and partial. This method uses the Taylor series approach to replace the derivative in a differential equation. The finite difference method has two scheme types, explicit and implicit. Numerically, the explicit scheme is easier to apply than the implicit one. The explicit scheme is also more effective in computational costs. Forward Time Centred Space, also known as FTCS, is one of the explicit finite-difference methods (FDM). The FTCS method uses a forward difference scheme for approximating the time derivative. On the other hand, the space or spatial derivative approximation uses the central difference scheme.

This study aims to see how the characteristics and patterns of flow due to partial dam failure and the presence of an obstacle in the floodplain. The research can provide insights into the behavior of water flow during dam failure and the presence of obstacles in the floodplain, which can help in developing strategies to mitigate the effects of floods and improve dam safety.

The FTCS method was used to develop a numerical model capable of simulating 2D partial dam-break flow with an obstacle on the floodplain. Furthermore, the developed FTCS model is added to a numerical filter, the Hansen filter. The advantage gained from adding the numerical filter is the increased stability of the model, as shown by Adityawan and Tanaka (2012), Hafiyyan et al. (2021), Mellivera et al. (2020), Maitsa et al. (2020), and Zendrato et al. (2019). In this study, the model was applied to complex dam-break cases. The case is a 2D partial dam-break with an obstacle located downstream of the dam. That obstacle can be assumed as a building. This case is commonly known as an urban dam-break. Because the analytical solution of this case is not available, the results are compared with the simulation results of previous studies (Baghlani, 2011; Wang et al., 2000).

METHOD

Governing Equations

The equation commonly used to describe dam-break flow is shallow-water equations (SWEs). This equation is a set of hyperbolic equations obtained from the integration of Navier-Stokes average depth equations. The shallow-water equations include continuity and momentum equations. The 2D shallow-water equations (SWEs) can be expressed as follows (ignoring the effects of Coriolis forces, wind, turbulence, and viscosity):

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial h}{\partial x}-g(So_x-Sf_x)=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial h}{\partial y}-g\left(So_y-Sf_y\right)=0 \tag{3}$$

Where h is the depth of water, u and v are the velocity flows of a two-dimensional, g is the gravity acceleration, Sox and Soy are the bottom slopes in two directions, Sfx and Sfy are the energy grade lines in two directions. Using Manning's formula, the energy grade lines can be obtained using the following equation:

$$Sf_x = \frac{n^2 u\sqrt{u^2 + v^2}}{h^{4/3}} \quad (4)$$

$$Sf_y = \frac{n^2 v\sqrt{u^2 + v^2}}{h^{4/3}} \quad (5)$$

With n is Manning's roughness value. Meanwhile, the bed slopes in two directions is defined as follows:

$$So_x = -\frac{\partial z}{\partial x} \quad (6)$$

$$So_y = -\frac{\partial z}{\partial y} \quad (7)$$

With z is channel bed height.

Discrete Form of Governing Equation

The shallow-water equations (SWEs) are solved using an explicit finite difference method, the FTCS method. This method uses a first-order forward difference approach for time derivatives. Meanwhile, space derivatives use the central difference approach. For example, equations 2, 3, and 4 are the approximate results of the FTCS method for each term in equation 1.

$$\frac{\partial h}{\partial t} = \frac{h_{i,j}^{t+1} - h_{i,j}^{t}}{dt} \quad (8)$$

$$\frac{\partial hu}{\partial x} = \frac{h_{i+1,j}^{t}\, u_{i+1,j}^{t} - h_{i-1,j}^{t}\, u_{i-1,j}^{t}}{2\, dx} \quad (9)$$

$$\frac{\partial hv}{\partial y} = \frac{h_{i,j+1}^{t}\, v_{i,j+1}^{t} - h_{i,j-1}^{t}\, v_{i,j-1}^{t}}{2\, dy} \quad (10)$$

The discrete form of the governing equation is as follows:

$$h_{i,j}^{t+1} = h_{i,j}^{t} - k_x\left(h_{i+1,j}^{t}\, U_{i+1,j}^{t} - h_{i-1,j}^{t}\, U_{i-1,j}^{t}\right) - k_x\left(h_{i,j+1}^{t}\, V_{i,j+1}^{t} - h_{i,j-1}^{t}\, V_{i,j-1}^{t}\right) \quad (11)$$

$$\begin{aligned} u_{i,j}^{t+1} = u_{i,j}^{t} - k_x u_{i,j}^{t}\left(u_{i+1,j}^{t} - u_{i-1,j}^{t}\right) - k_y v_{i,j}^{t}\left(u_{i,j+1}^{t} - u_{i,j-1}^{t}\right) - k_x g\left(h_{i+1,j}^{t} - h_{i-1,j}^{t}\right) \\ + g(So_x - Sf_x)dt \end{aligned} \quad (12)$$

$$\begin{aligned} v_{i,j}^{t+1} = v_{i,j}^{t} - k_x u_{i,j}^{t}\left(v_{i+1,j}^{t} - v_{i-1,j}^{t}\right) - k_y v_{i,j}^{t}\left(v_{i,j+1}^{t} - v_{i,j-1}^{t}\right) - k_x g\left(h_{i,j+1}^{t} - h_{i,j-1}^{t}\right) \\ + g\left(So_y - Sf_y\right)dt \end{aligned} \quad (13)$$

Where

$$k_x = \frac{dt}{2\ dx} \tag{14}$$

$$k_y = \frac{dt}{2\ dy} \tag{15}$$

Numerical Filter

The Hansen filter is coupled to the FTCS model. It aims to address the oscillation problem in the model that arises due to the shock wave. In addition, numerical filters are also used to obtain stable simulation results. The principle of the Hansen filter is to filter flow parameters such as depth and flow velocity at each time iteration. The filter process is carried out using the following equation:

$$F_{i,j} = C \times F_{i,j} + (1 - C)\left(\frac{F_{i-1,j} + F_{i+1,j} + F_{i,j-1} + F_{i,j+1}}{4}\right) \tag{16}$$

C is a correction factor whose value ranges from 0 to 1, and F is filtered flow parameters such as depth and flow velocity. Based on previous studies (Zendrato et al., 2019), this study uses a correction factor of 0.99. Based on equation 16 and the value of C, the equation obtained to filter each flow parameter is as follows:

$$h\ filter_{i,j} = 0{,}99 \times h_{i,j} + 0.01\left(\frac{h_{i-1,j} + h_{i+1,j} + h_{i,j-1} + h_{i,j+1}}{4}\right) \tag{17}$$

$$u\ filter_{i,j} = 0{,}99 \times u_{i,j} + 0.01\left(\frac{u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1}}{4}\right) \tag{18}$$

$$v\ filter_{i,j} = 0{,}99 \times v_{i,j} + 0.01\left(\frac{v_{i-1,j} + v_{i+1,j} + v_{i,j-1} + v_{i,j+1}}{4}\right) \tag{19}$$

RESULT AND DISCUSSION

Another case is a two-dimensional (2D) partial dam break with a rectangular obstacle. This problem has been studied in Baghlani (2011) and Wang et al. (2000). The computational domain of this case is 500 m long (x-direction) and 200 m wide (y-direction). In this case, a dam at x = 250 m is assumed to collapse suddenly. In addition, there is a rectangular obstacle (40 m x 50 m) located 125 m after the dam. Obstacle positions are 110 m from the left side of the domain or 140 m from the right side. In initial conditions, the depth and flow velocity in the upstream area are 10 m and 0 m/s (calm), respectively. The water in the downstream part of the dam has a depth of 2 m and is also in a calm condition. In this case, each edge of the computational domain is assumed to be reflective. Another assumption is that the bottom of the channel has zero slopes and is frictionless. The initial conditions of this case can be seen in Figure 1.

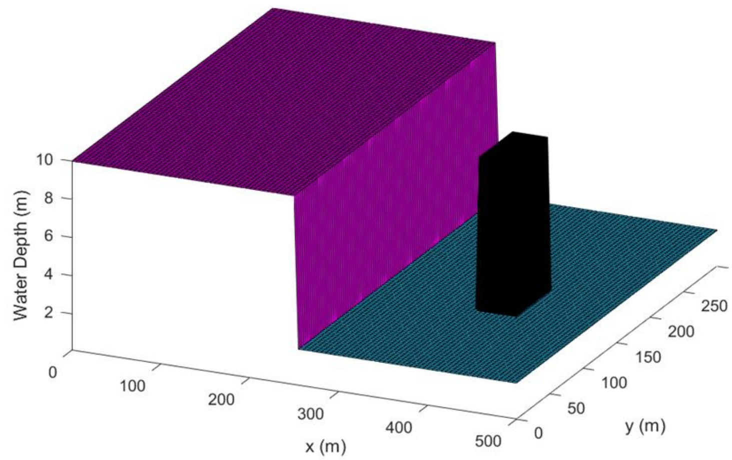

Figure 1. Initial Condition t = 0 Seconds

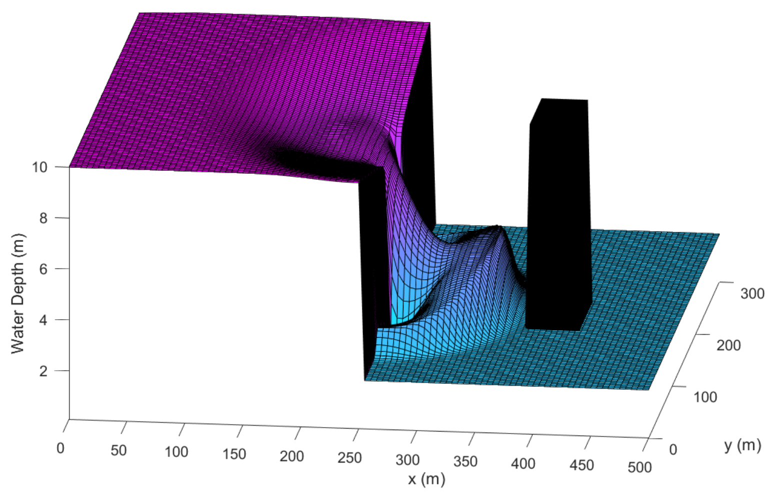

Figure 2. The Calculated Water Surface Profile at t = 12 Seconds

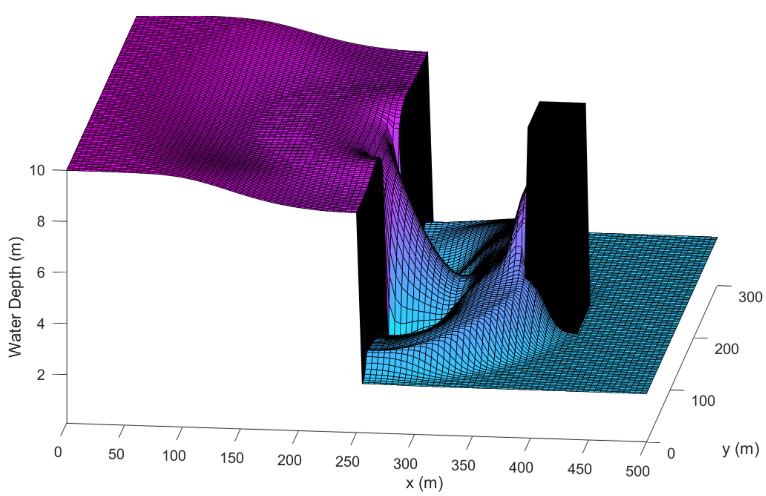

Figure 3. The Calculated Water Surface Profile at t = 18 Seconds

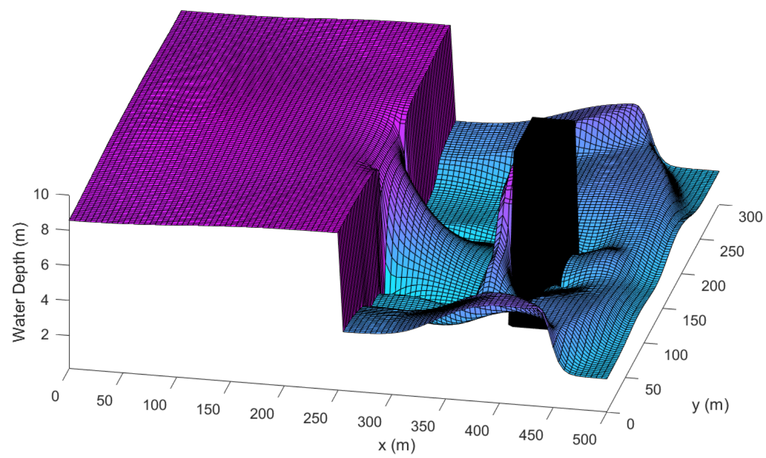

Figure 4. The Calculated Water Surface Profile at t = 32 Seconds

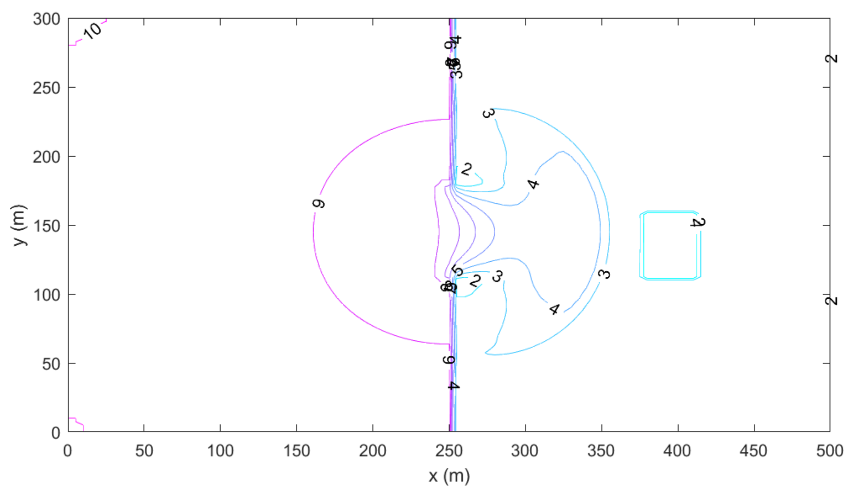

Figure 5. The Depth Contour of the Water at t = 12 s

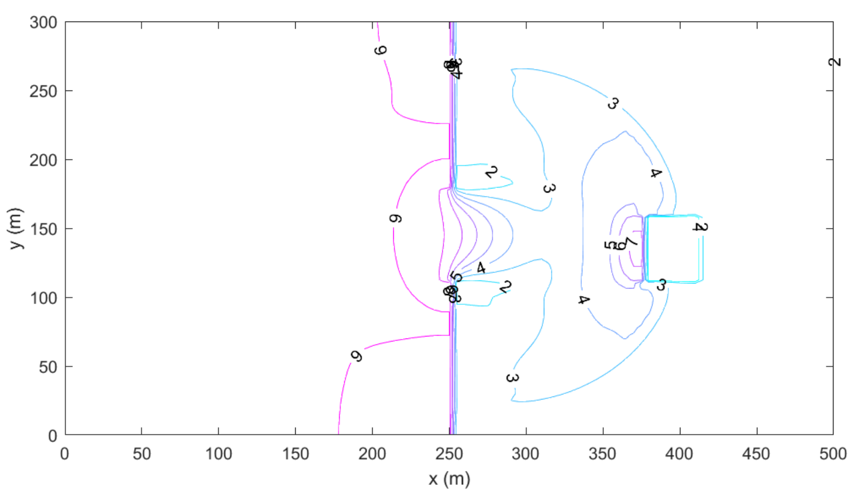

Figure 6. The Depth Contour of the Water at t = 18 s

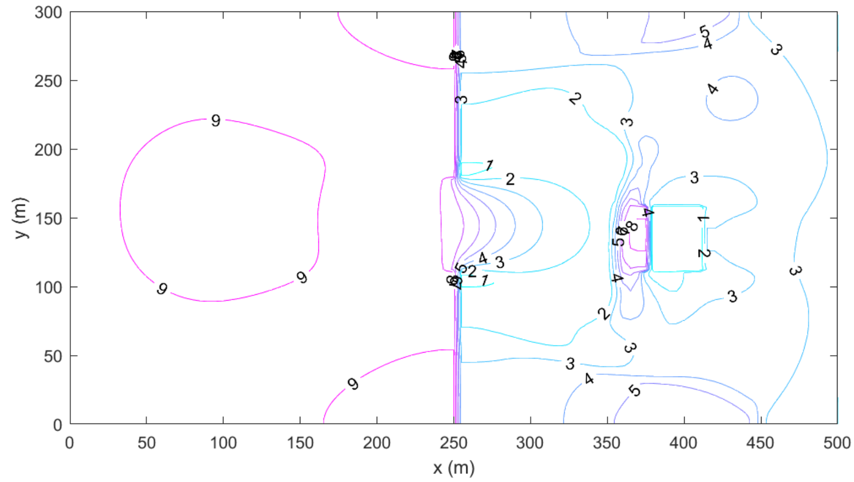

Figure 7. The Depth Contour of the Water at t = 32 s

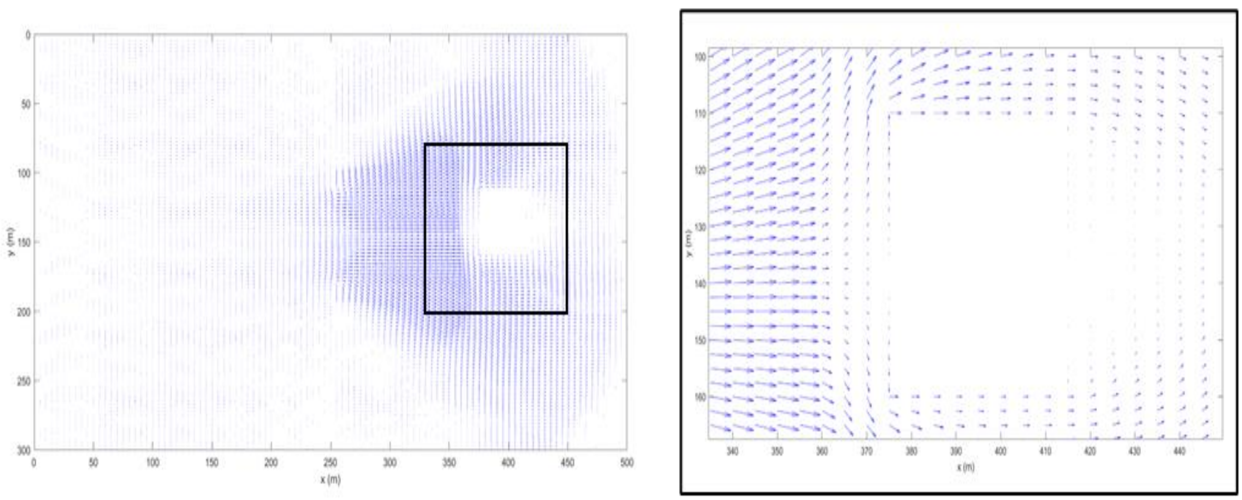

Figure 8. Velocity Vector at t = 32 s

The simulation results using the FTCs-Hansen model at t = 12s, 18s, and 32s can be seen in Figures 2 to 4. The simulation results of the FTCS-Hansen model are in good agreement with previous studies (Baghlani, 2011; Wang et al., 2000). Figure 2 shows the conditions where the dam-break flow before hitting an obstacle. Figures 3 and 4 show how the dam-break flow pattern is when it hits an obstacle. From the two figures, it can be seen that when a wave hits an obstacle, the wave moves around the obstacle and then forms a new discontinuity. In addition, the obstacle also causes the water level in front of the obstacle to rise. Figures 5, 6, and 7 show the contours of the water level at three different times (12s, 18s, and 32s). Wave interactions after the waves hit and go around the obstacle are shown in Figure 7. Figure 8 shows the velocity vector when the time is 32 seconds. The figure clearly shows a change in the direction of flow (reflection) when it collides with an obstacle.

CONCLUSION

In the present study, a finite-difference model is used to simulate the dam-break flow problem. The problem is a two-dimensional (2D) partial dam-break with an obstacle in the downstream area (floodplain). The purpose of the simulation is to examine the characteristics and patterns of the flow that occurs. In addition, the effect of obstacles on the flow due to dam failure is also studied. The proposed model is based on the FTCS scheme coupled with the Hansen Filter. The FTCS scheme uses a first-order forward difference formula to solve the time derivative. Next, the central difference formula is to complete the space derivative. A numerical filter on the model is added to handle numerical oscillations due to the discontinuity of the dam-break. Next, the computational results are compared with computational results from other studies. Overall, the results from the FTCS-Hansen model show a satisfactory agreement with other numerical models. In addition, this model was able to capture well the movement and pattern of dam-break flow colliding with obstacles. In this study, the FTCS-Hansen model has been proven capable of simulating a dam-break flow with flat and fixed beds. The next step is to test the FTCS-Hansen model for dam-break problems with a complex topography and movable bed.

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