

2D Hydrodynamic Simulation Model for Dam-Break Based on the Finite Difference Method

by

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Abstract

Dam-break disasters keep happening many times each year all over the world. Examples from 2018 to early 2019 include the Brumadinho dam in Brazil, Swar Chaung dam in Myanmar, Xe-Pian Xe-Namnoy dam in Laos, Panjshir Valley dam in Afghanistan and Patel dam in Kenya. Each of these dam-breaks caused hundreds of fatalities or missing persons, with thousands of others being made homeless. The fact that causes of dam-breaks differ means that they are inevitable, therefore governments or companies that are responsible for the safety of a dam should always consider preparing hazard maps. Accordingly, investigation and research on dam-breaks are crucially important. This paper presents a two-dimensional simulation model assuming a rectangular-shape dam-break section of a dam with a reservoir. The model can calculate flow velocity and inundation heights at various time points from the time of the break. The hydrodynamics of the model are calculated using two-dimensional nonlinear shallow water equations, which are solved by the finite difference method. To verify the applicability of the model, the tsunami caused by the 2011 Great East Japan Earthquake is simulated in the Sendai-Natori area with acceptable relative accuracy, and then the Amagase dam-break is simulated as an example.

Keywords: Shallow water equation, Dam-break model, Long-wave flood, Hydrodynamic simulation model

1. Introduction

There are many hydrodynamic simulation models for a dam-break scenario, which are capable of simulating both 2D and 3D models. To name a few of the accurate models for simulation of the flood due to a dam-break. HEC-RAS V.5, MIKE 21 and TUFLOW models are among the most famous flood simulation models that are available for either educational or business purposes. These software can evaluate the extent of the flooded area, flood distribution depths at times, flood velocities at times, flood arrival times to target locations, and the respected flood duration. These software are already extensively being used for different hydrodynamic flood simulation purposes and there are many researchers who

have confirmed their accuracy specifically for dam-break scenarios like “Landslide dam and subsequent dam-break flood estimation using HEC-RAS model in Northern Pakistan” (Butt, Umar, and Qamar 2013)¹.

To verify the dam-break simulation model, we need real case dam-break data to compare the simulation results with them and then discuss the accuracy of the model. Because it is difficult to find and measure the hydrodynamic data in case of a dam-break, in this paper, we introduce a flood simulation model that we had developed for tsunami simulations and have confirmed its reproducing ability by simulating some flood cases due to existing tsunamis. Because in the literature, floods due to a tsunami and a dam-break are categorized into the same long-wave motion or in other words, a flood is expressed with the same motion equation as that of tsunami since the flood is the plane 2D nonlinear long-wave like a tsunami. Therefore, we have only to input water from the mountainside instead of inputting water from the sea. Moreover, existing numerical models developed for a river flow are applicable only to movement, which always flows

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from the upstream side to the downstream side of the river. However, when the flood overflowed out of the river, since a device to run-up process is necessary at uphill places, we had better use the numerical model for tsunami, which is applicable to uphill places. With this in mind, we could modify our model for dam-break flood-simulation purpose with minor changes on an input method. Our proposed model solves the continuity equation (Eq.(1)) and the two-dimensional nonlinear shallow water equation (Eq. (2&3)), by finite difference method using the Crank-Nicholson scheme. As a numerical simulation method using a digital computer, since use of FDM is the very rational, FDM has been vastly used in numerical simulations of the hydrodynamics field, and many support programs exist. Therefore, we adopted FDM. For the data input purpose of the model, we need to have the real topography of downstream of the dam to the desired extent. It is worth mentioning that the wider we choose the target area, the higher capacity of workstation-computer is required. The model has a side application software (CONTWIN) which is able to convert Digital Elevation Models (DEM) or DXF format of topography maps into the desired grids. The accuracy of the calculations can be controlled based on the mesh size we choose in this step. Break dimension (width and height), dam basin area and discharge volume, calculation range, desired calculation time interval, land use data (the ratio of buildings, forests, cultivation and flat area in a mesh) are input data sets.

To confirm the accuracy of the proposed model in the case of hydrodynamics, the flood simulation due to a tsunami is executed on the Sendai-Natori area.

To confirm the workability of our simulation model, we chose Amagase dam, located in Kyoto Prefecture of Japan as a sample dam-break scenario. The main purpose of the Amagase dam is flood control and the dam was constructed in 1964. The dam is a 73 m tall, 254 m long variable-radius arch type with a structural volume of 162,000 m³. The dam withholds a reservoir called Lake Hōō (Hōō-ko, lit. "Lake Phoenix") of 26,280,000 m³ of which 20,000,000 m³ is active or "useful" storage. It has a surface area of 1.9 km² and it is worth mentioning that at the downstream of Amagase Dam, there is a densely populated residential area of over 100,000 individuals which can be a reason for this simulation.

2. Calculation Methods

Since there are many numerical methods for dam-break flows. They can be classified into three broad types: finite-difference methods, finite-element methods, and finite volume methods (Zhang and Wu 2011)²⁾. In this paper, we have used the finite-difference method to solve the hydrodynamic

equations. For hydrodynamic calculations, we have used the popular equation of continuity (Eq.(1)) and two-dimensional nonlinear shallow water equations (Eq. (2 & 3)).

$$\frac{\partial f_y q_x}{\partial x} + \frac{\partial f_x q_y}{\partial y} + \frac{\partial S \eta}{\partial t} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial q_x}{\partial t} + \frac{1}{S} \frac{\partial}{\partial x} \left(\frac{S q_x^2}{d} \right) + \frac{1}{S} \frac{\partial}{\partial y} \left(\frac{S q_x q_y}{d} \right) + \\ g d \frac{\partial \eta}{\partial x} - \frac{1}{S} \frac{\partial}{\partial x} \left[d \nu_t S \frac{\partial (q_x / d)}{\partial x} \right] - \end{aligned} \quad (2)$$

$$\frac{1}{S} \frac{\partial}{\partial y} \left[d \nu_t S \frac{\partial (q_x / d)}{\partial y} \right] + \frac{f_c}{d^2} Q q_x = 0$$

$$\begin{aligned} \frac{\partial q_y}{\partial t} + \frac{1}{S} \frac{\partial}{\partial x} \left(\frac{S q_y q_x}{d} \right) + \frac{1}{S} \frac{\partial}{\partial y} \left(\frac{S q_y^2}{d} \right) + \\ g d \frac{\partial \eta}{\partial y} - \frac{1}{S} \frac{\partial}{\partial x} \left[d \nu_t S \frac{\partial (q_y / d)}{\partial x} \right] - \end{aligned} \quad (3)$$

$$\frac{1}{S} \frac{\partial}{\partial y} \left[d \nu_t S \frac{\partial (q_y / d)}{\partial y} \right] + \frac{f_c}{d^2} Q q_y = 0$$

Where q_x & q_y are the horizontal fluid fluxes in the x & y directions respectively. η is the water surface elevation, f_x & f_y are the x & y direction ratios of the wet portion in a calculation mesh. S is the area ratio of the wet portion in a calculation mesh. d is the water depth from the static water surface η . g is the gravitational acceleration, ν_t is the eddy viscosity coefficient. $Q = \sqrt{q_x^2 + q_y^2}$ is the compound value of q_x & q_y . To calculate the bottom friction coefficient, the following equations are used;

$$f_c = \frac{g n^2}{d^{1/3}} \quad (4)$$

$$n^2 = n_0^2 + 0.020 \frac{\theta}{100 - \theta} d^{4/3} \quad (5)$$

$$n_0^2 = \frac{n_1^2 A_1 + n_2^2 A_2 + n_3^2 A_3}{A_1 + A_2 + A_3} \quad (6)$$

Here, n is the Manning's roughness coefficient. θ is the building ratio (= the ratio of the area of all vertical objects like houses and trees to the mesh area). n_0 is the weighted average roughness coefficient of areas like farms, roads, and waste& wetlands, $A_{1,2,3}$, with relative roughness coefficients of $n_{1,2,3}$.

The cause for a dam-break is varied in each dam-break case where the most common causes can be great earthquakes, overtopping due to heavy flash floods (this failure cause is expected to increase in the following decades due to climate changes) and the aging of a dam. A more complete list of the most prominent causes of dam-break are listed in the US Army Corps of Engineers Hydrologic Engineering Center, Flood Emergency Plans, Guidelines for Corps Dams as (1)

Earthquake; (2) Landslide; (3) Extreme storm; (4) Piping; (5) Equipment malfunction; (6) Structure damage; (7) Foundation failure; (8) Sabotage (Owen 1980)³). For each of these different failure causes, the break sections may vary which means the discharge rate is sentenced to change as well. This change in the rate of discharge makes the simulation and accurate calculations very complex. Many researchers have already developed models to simulate the dam breach scenarios on different types of dams and as well as different failure cases. “Methodology for Earthen Dam Breach Analysis” (Yue Sheng, Damisse Emile, and Ansar Matahel 2016)⁴), “Hydrodynamic Dam Breach Modelling of Earthfill Saddle Dam” (Sidek 2011)⁵), “Analysis of Hydrograph by Dam Breach Shapes” (ki-bum Park 2019)⁶) are some of the papers which concentrates more on the failure shapes and the discharge rates of different dam type’s failure with various break sections, however, in this paper, the main focus is the flood plain and hydrodynamics calculations following a dam-break. For this purpose, we have assumed a trapezoidal break section and derived new equations for calculating a run-off rate to this dam-break as follows;

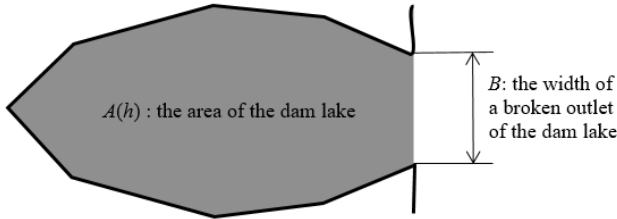


Fig. 1 Dam-break section plan view.

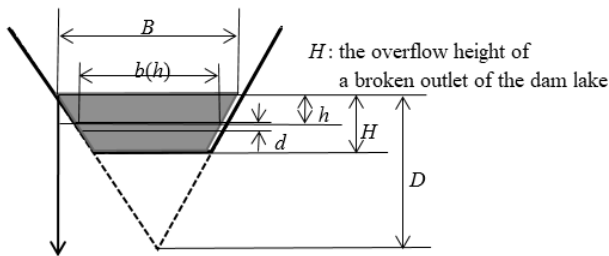


Fig. 2 Dam-break cross-section view.

The run-off rate from the dam lake in the case that the overflow height H is constant (water supply is infinite) can be calculated from bellow equations;

$$Q = \int_0^H b(h) \times c\sqrt{2gh} dh = \int_0^H \frac{B(D-h)}{D} c\sqrt{2gh} dh \quad (7)$$

$$Q = \frac{B}{D} c\sqrt{2gh} \left[D \frac{2}{3} h^{3/2} - \frac{2}{5} h^{5/2} \right]_0^H \quad (8)$$

$$Q = \frac{B}{D} c\sqrt{2g} \left(\frac{2}{3} DH^{3/2} - \frac{2}{5} H^{5/2} \right) \quad (9)$$

Since the case of finite water supply from a dam lake is more realistic in the actual dam-break cases, in this paper, we have used the equation for run-off rate from the dam lake by following equations;

$$Q = A(h) \times \frac{dh}{dt} \quad (10)$$

$$Q = \frac{B}{D} c\sqrt{2g} \left(\frac{2}{3} D \left(H - \frac{dh}{dt} T \right)^{3/2} - \frac{2}{5} \left(H - \frac{dh}{dt} T \right)^{5/2} \right) \quad (11)$$

Here, T is the run-off elapse time (sec), V is the total volume of discharge water, and c is the flow rate coefficient ($=0.61$).

$$V = \int_0^H A(h) dh = \int_0^{\frac{H}{dh/dt}} Q dT \quad (12)$$

$$V = \int_0^{\frac{H}{dh/dt}} \frac{B}{D} c\sqrt{2g} \left(\frac{2}{3} D \left(H - \frac{dh}{dt} T \right)^{3/2} - \frac{2}{5} \left(H - \frac{dh}{dt} T \right)^{5/2} \right) dT \quad (13)$$

$$= \frac{B}{D} c\sqrt{2g} \frac{1}{dh/dt} \int_H^0 \left(\frac{2}{3} DX^{3/2} - \frac{2}{5} X^{5/2} \right) dX \quad (14)$$

$$= \frac{B}{D} c\sqrt{2g} \frac{1}{dh/dt} \left[\frac{4}{15} DX^{5/2} - \frac{4}{35} X^{7/2} \right]_H^0 \quad (15)$$

$$\text{Here, } X = H - \frac{dh}{dt} T \quad (16)$$

$$\frac{dX}{dT} \approx \frac{dh}{dt}, T = 0 \rightarrow T = \frac{H}{dh/dt}, X = H \rightarrow X = 0 \quad (17)$$

Thus,

$$\therefore V = \frac{B}{D} c\sqrt{2g} \frac{1}{dh/dt} \left(\frac{4}{15} DH^{5/2} - \frac{4}{35} H^{7/2} \right) \quad (18)$$

$$\therefore \frac{dh}{dt} = \frac{Bc\sqrt{2g}}{DV} \left(\frac{4}{15} DH^{5/2} - \frac{4}{35} H^{7/2} \right) \quad (19)$$

$$\therefore T_{total} = \frac{H}{dh/dt} = \frac{DV}{Bc\sqrt{2g}} \frac{1}{\frac{4}{15} DH^{5/2} - \frac{4}{35} H^{7/2}} \quad (20)$$

Here, D is the imaginary depth from the dam crown height and it is assumed 1000m in this simulation.

3. Hydrodynamic verification

For the hydrodynamics verification calculations of our proposed model, the great tsunami of the 2011 Japan earthquake is simulated in the Sendai-Natori area. The destination area is located in Miyagi Prefecture of Japan, where Sendai City is on the north of Natori River and Natori City on the south. Natori River is flowing to the Pacific Ocean, west-east. Fig. 3 shows the existing topography of the area. The ground height from the coastline of less than 4 km is very low. Fig. 4 shows the area ratio of buildings or trees to a mesh, the dark area larger than 30 percent means the area occupied by buildings, the green area larger than 5 percent is the forest area, the yellowish-green area larger than 1 percent is the cultivated & paddy area, and the white area is the sea area. In the numerical simulation model, the mesh size was 25 m.

The incident tidal data on the offing boundary line of this

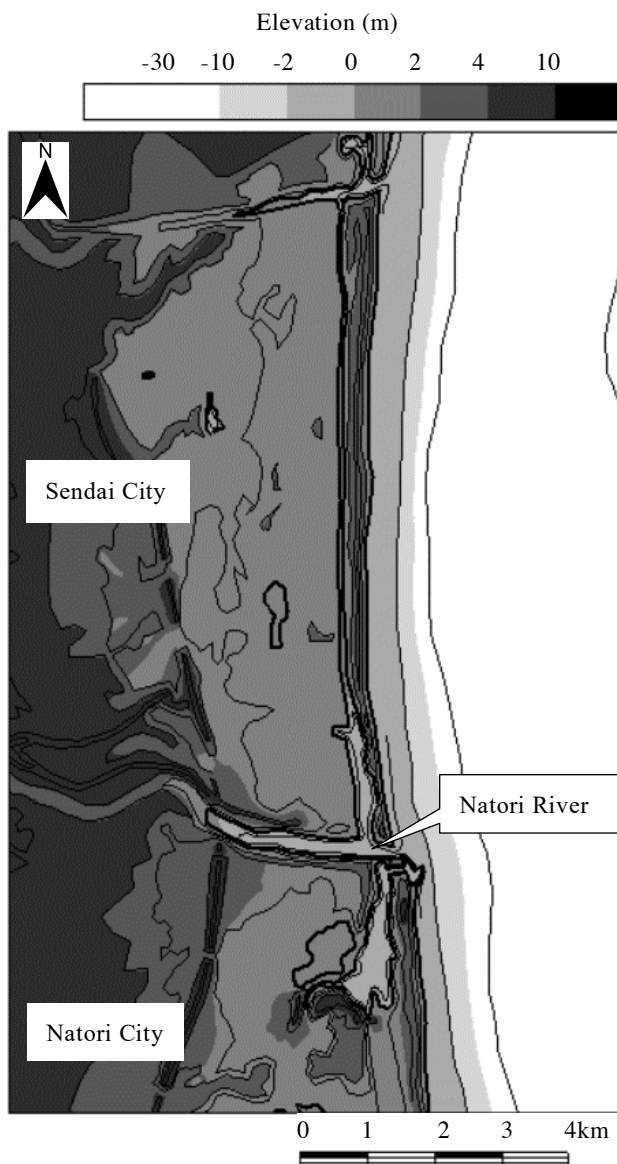


Fig. 3 Topography of calculation area (Sendai - Natori Coast). simulation was set with reference to Fig. 3.2.3 of Technical Note No.1231 of PARI (2011)⁷⁾. However, since missing data

are in the tidal data on the offing of Miyagi Prefecture, average data between Fukushima Prefecture and Iwate Prefecture were used. Moreover, the maximum tidal height on the offing boundary line was estimated to be 10 m, and the time of the incident phase & the whole period of the first wave became 30 minutes and 48 minutes respectively. The maximum tsunami height on the shoreline appears after about 28 minutes of the calculation start, and according to Fig. 5 which shows the water depth in the sea and the inundation height on the land after 28 minutes, the maximum height on the shoreline is 6~12 m. On the other hand, according to Figs. 5.3.8.1~5.3.8.4 of Technical Note No.1231, measured maximum tsunami height is 6~12 m, so the reproduction accuracy of the calculated height is good. The maximum velocity near the coastline is 6~10 m/s as shown in Fig.6 which shows the tsunami velocity in on-offshore direction after 28 minutes. On the other hand, according to Fig. 3 in the paper of Hayashi et al. (2013)⁸⁾, since

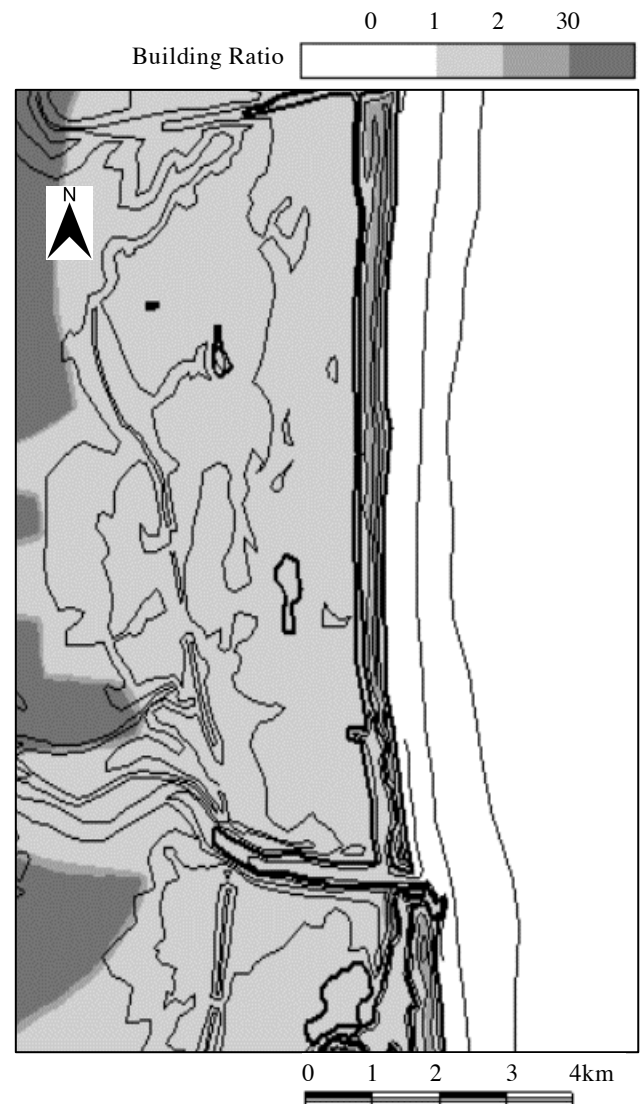


Fig. 4 Area ratio of buildings or trees to a mesh.

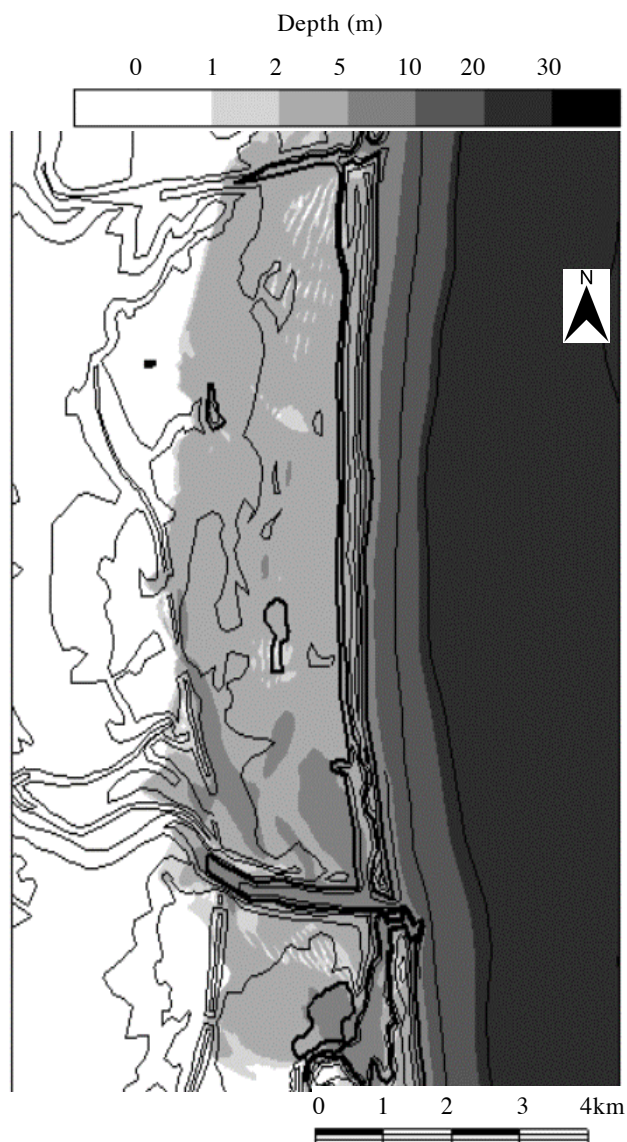


Fig. 5 Water depth in the sea and inundation height of the land after 28 minutes of the calculation start.

the measured maximum velocity near the coastline is 5~8 m/s, the reproduction accuracy of the calculated velocity is moderately good.

4. Amagase Dam-Break Simulation

Amagase Dam is located in Uji city in Kyoto Prefecture Japan. Fig. 7 shows its location on google map. For the break simulation purpose, the height and width of the broken section of Amagase Dam are assumed 50m and 200m respectively. The area of the dam lake is considered as 1,880,000 square meters. Although this dam is not a mega-scale dam when we compare it to other huge dams in the world, it's worth mentioning that, around 100,000 individuals are living downstream of it, where if the dam-breaks, a catastrophic disaster is predictable which makes this practice simulation model a more demanding case.



Fig. 6 Tsunami velocity after 28 minutes of the calculation start.

Fig. 8 shows the topography map and the calculation range, which are used in the simulation. As it is common by other simulation software, our proposed model uses the existing Digital Elevation Models (DEMs) available now worldwide with relatively different accuracies. For this simulation, however, we have used a 10 m accuracy DEM for developing the existing topography meshes. The area ratio of buildings, dense forests or trees, cultivated or paddy area in a mesh is depicted in Fig. 9. (distribution of θ of Eq. (5)). The gray area means the area occupied by all types of buildings and the occupying ratio in a mesh is about 30 percent of a mesh area, the medium gray area shows the heavy forest area which relatively occupies up to 30 percent of a mesh area. The light gray area shows the category of other areas including grass area and light cultivated area. The white area shows the water area.

In the Amagase dam-break simulation model case, the mesh size was set to 20m. The output interval was set to every 60 seconds. The total duration of 2400 seconds was set as the calculation time limits.

Now that the input datasets are ready, using our numerical simulation model, we could generate a set of useful output data. Fig. 10 shows the inundation depths 40 minutes after the dam-break happens. The very light gray and gray color shows a depth of 1-5 meter inundation and dark gray shows a depth of 5-10 meter inundation while dark gray and black area shows depths of 10-20 meter of inundation. According to the inundation height output, a wave of 2-5 meters in height will most probably strike the nearby densely populated area at the downstream which can cause a catastrophic disaster.

Fig. 11 shows the flow velocity 20 minutes after the break. The flow velocity varies from zero to 10 meters per second, which the distribution is depicted by the gray color chart. It's worth mentioning that, since at this time, the amount of return flows (negative velocity) is very small, it is very difficult to distinguish, however, at later calculation times, the model can reproduce the return flows as well.

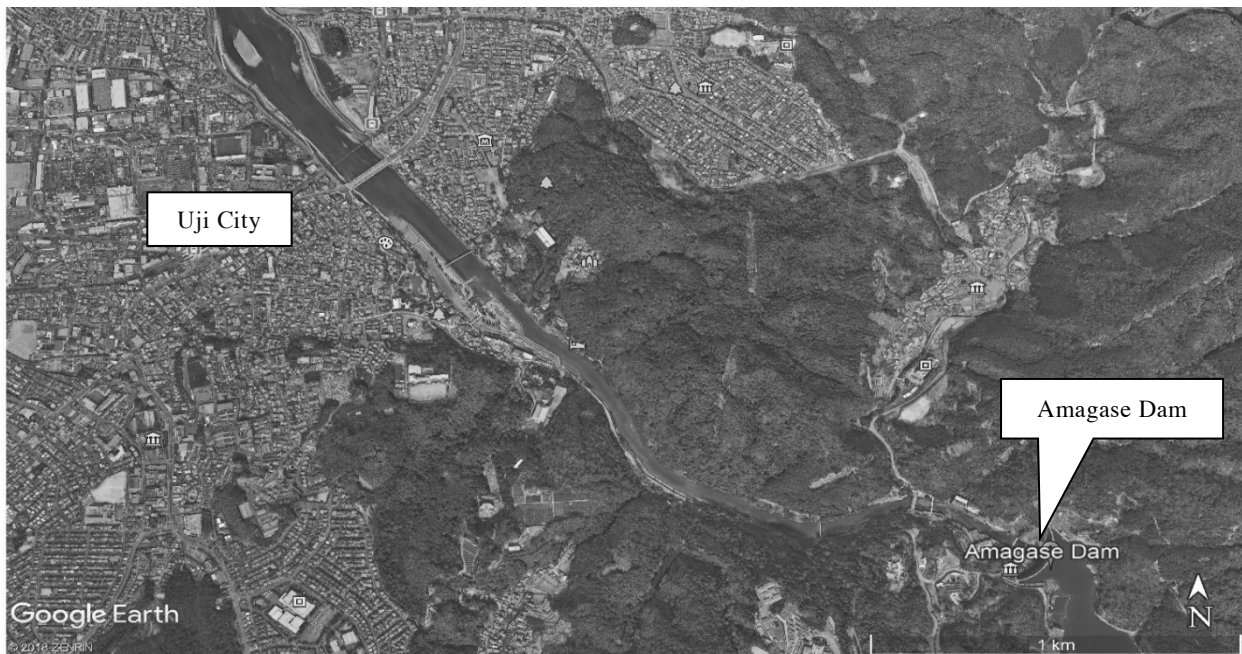


Fig. 7 Amagase dam location (google map).

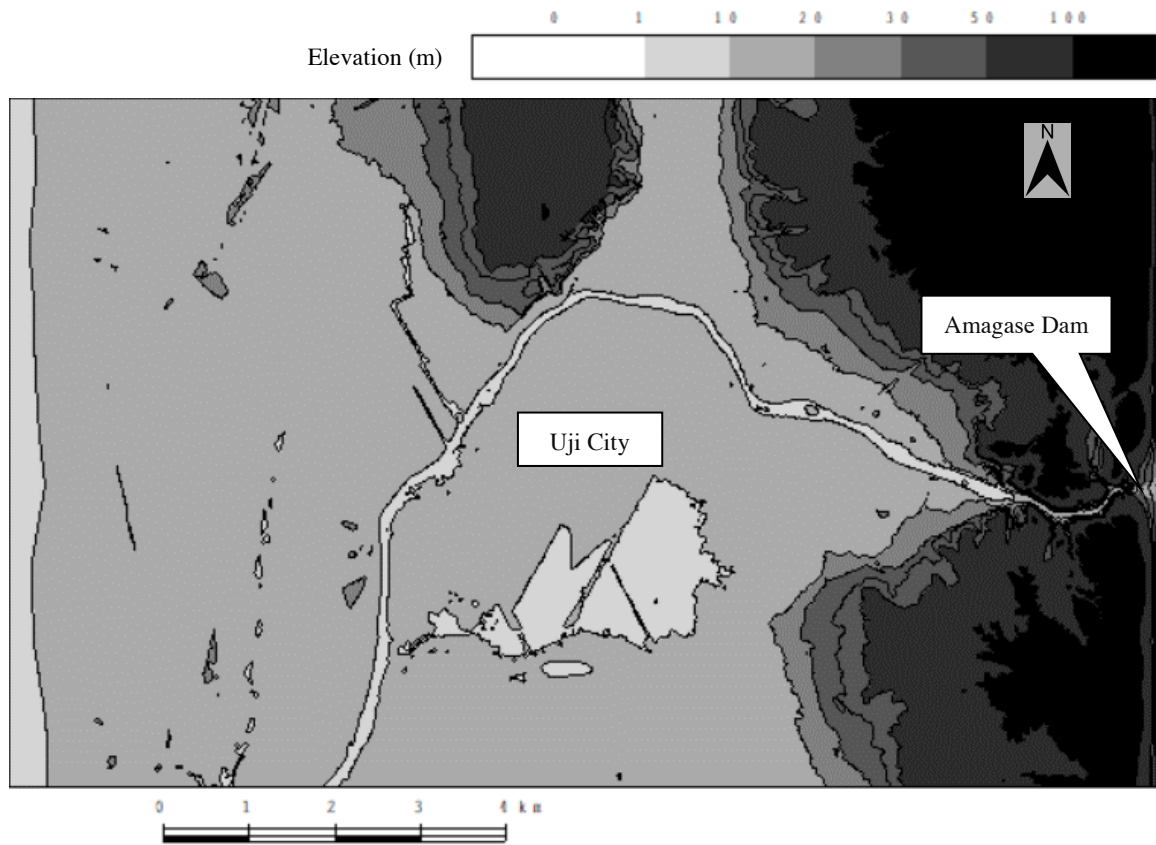


Fig. 8 Topographic map and calculation range.

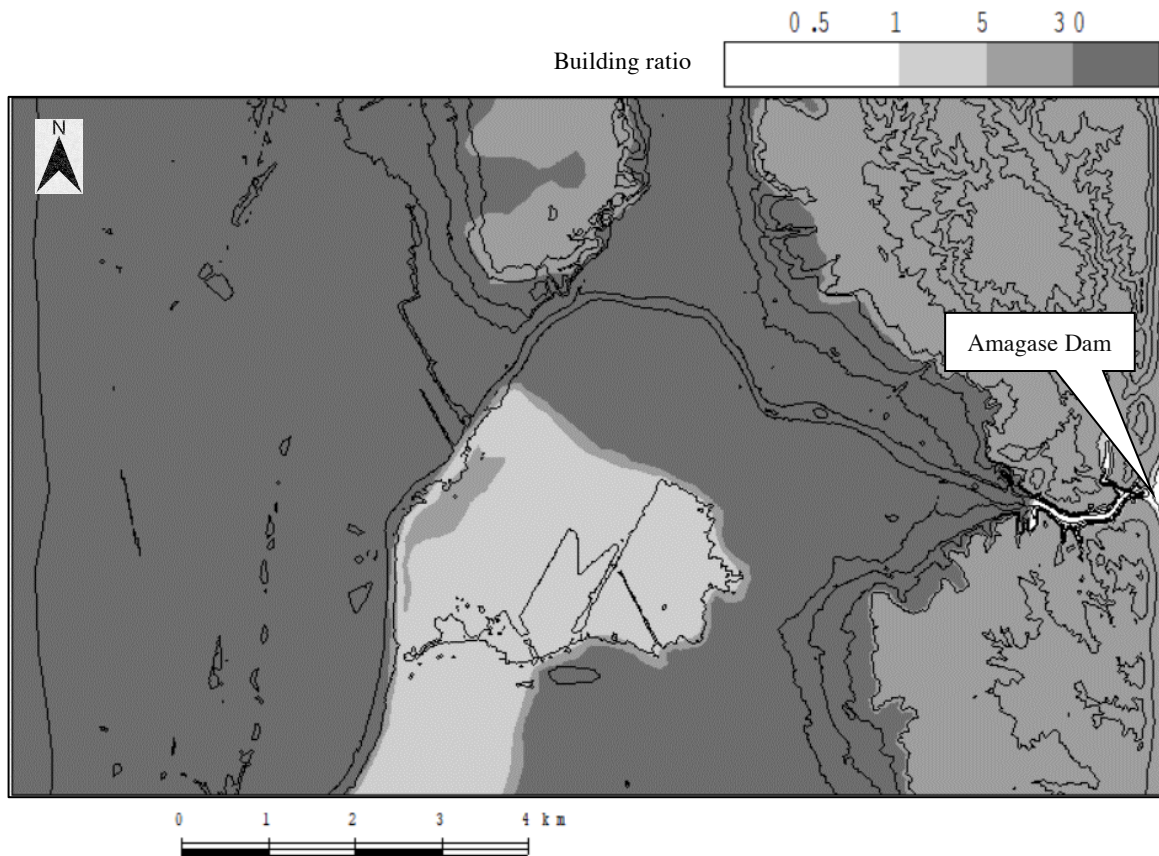


Fig. 9 Area ratio of buildings or trees to a mesh.

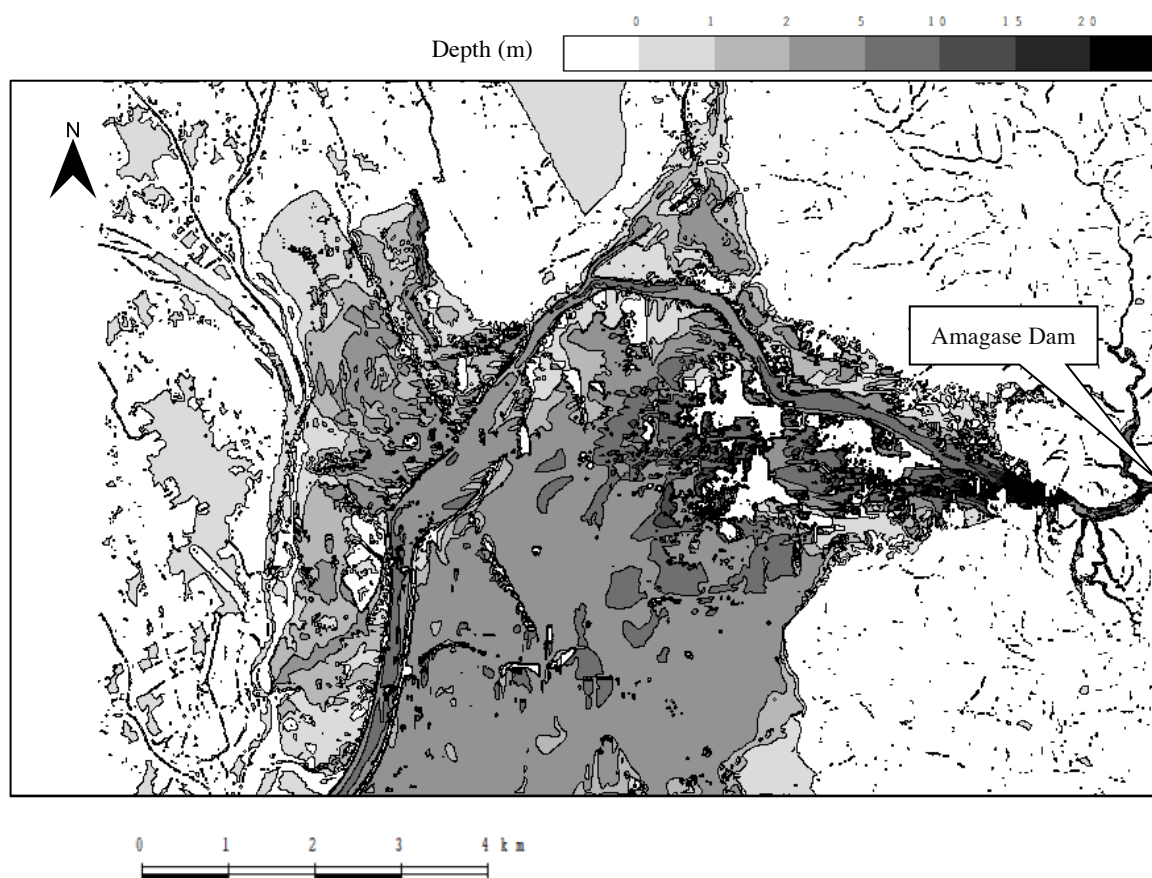


Fig. 10 Inundation depth 40 minutes after the break.

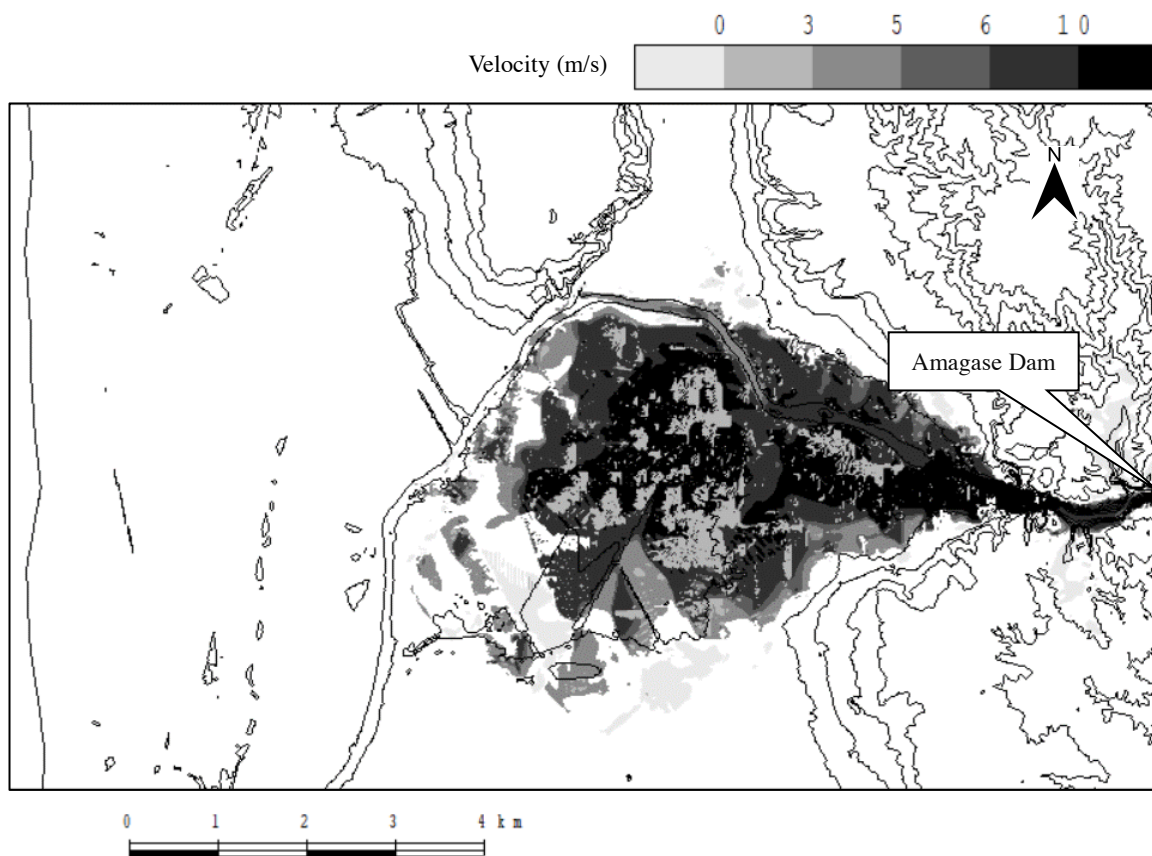


Fig. 11 Flow velocity 20 minutes after the break.

5. Conclusions

In the last decades, the life safety demand has increased in the world while hazards are increasing as well, to balance this situation; we need to focus on safety measures as far as possible. The dam-break or levee failure may lead to huge floods that cause catastrophic damage and life losses if proper considerations are not taken on time. A dam-break may occur due to many reasons such as heavy flush floods, aging, or sabotage. Hence, accurate flood simulation models must be developed which greatly helps in hazard map preparation. Many scientists have already developed flood simulation models either 2D or 3D, which can reproduce almost accurate floods due to dam-breaks, but since the number of variations is too many to consider in a single model, still this topic is under progression and development.

In this paper, a simulation model was presented which uses the common continuity equation and nonlinear two-dimensional shallow water equation for the hydrodynamic calculations. The flood simulation due to the 2011 Japan tsunami executed and evaluated with acceptable results to confirm the applicability of this model and then the same model was modified for the dam-break simulation scenario. For this purpose, the new run-off rate equations were derived and used for discharge calculations from a break section. To confirm the applicability of the proposed model, Amagase dam-breaks simulation is executed. The results of the simulation show the maximum inundation depth of about 20 meters and a wave of 2-5 meter in height will most probably strike the nearby densely-populated area at the downstream of Amagase dam which can cause a catastrophic disaster in case of a dam-break.

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