4th International Symposium on Flood Defence:
Managing Flood Risk, Reliability and Vulnerability
Toronto, Ontario, Canada, May 6-8, 2008

RAPID FLOOD SIMULATION SOFTWARE FOR PERSONAL COMPUTER WITH DYNAMIC DOMAIN DEFINING METHOD

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ABSTRACT: We developed global flood simulation software that simulates flood disasters in any areas in a short time on a personal computer. The two major technical challenges are (1) to prepare elevation data with global coverage and high accuracy and (2) to define the simulation area in which any flood disasters can be simulated. To prepare data, we propose a geographical information system (GIS) which manages spatial data according to time, location, and accuracy. The GIS stores multiple elevation data which overlap each other with different accuracies and the GIS retrieve most accurate data in stored data. To define the simulation area, we propose a calculation method named Dynamic Domain Defining Method (DDM). Because the simulation is conducted only in the simulation area, flooded area must always be included in the simulation area. In the conventional method, the user has to define the simulation area in advance of the simulation. Meanwhile in the Dynamic DDM, areas around a flooded area are automatically included in the simulation area, and the nonflooded areas are automatically excluded from the simulation area. Elevation data in the area which is newly included in the simulation area is automatically loaded from the GIS. At present, the software can simulate a flood disaster in major Japanese cities with 5-m horizontal resolution terrain data, in the entire area of Japan with 50-m horizontal resolution terrain data, in the entire land area on the earth with 90-m horizontal resolution terrain data. A simulation result of Fukui flood disaster adequately corresponds with a site investigation, and computational time for the simulation is less than 30 minutes in a laptop computer. As the next step, we need more validation of the simulation results and case studies of the use of the software.

Key words: Flood simulation software; Geographic information system; Shallow-water equations; Dynamic DDM; Visualization.

1. INTRODUCTION

Flood simulation software plays a significant role in river engineering, flood forecasting, and insurance. Actually, several software packages are commonly used in those filed (Fred et al., 2001). Markar et al. (2004) evaluated the accuracy and computational time of several popular packages for an integrated real-time flood forecasting system and concluded that all packages satisfied criteria specified in the Chinese National Standards. According to development of information technology, the software is required to be a more convenient tool for users. Now, most of those packages provide good user interface and are operated on a personal computer.

In addition, data needed for flood simulation are easily obtained. Digital elevation model (DEM) is the most important data for flood simulation. DEM data with wide coverage and high accuracy become available for many areas (Garbrecht et al., 2001). For example, the entire land area in Japan is covered by a DEM with 50-m horizontal and 1-m vertical resolution. In the US, a DEM with 30-m horizontal resolution is available from the United States Geological Survey (USGS). Recently, a more accurate DEM obtained with aerial laser scanning based on light detection and ranging (LIDAR) technology is available for many areas. For example, the LIDAR DEM data in major cities with 5-m horizontal and 0.1-m vertical resolution are available from the Geographical Survey Institute Japan. Large areas along major Japanese rivers are surveyed with 1- or 2-m horizontal resolution with the LIDER technology by the government. In addition, satellites which can obtain DEM with wide data coverage were launched. For example, Advanced Land Observing Satellite (ALOS) is designed to obtain DEM data with less than 5-meter errors, 10-meter horizontal resolution, and global coverage (Takaku et al., 2004). It is expected that DEM data with global coverage and high accuracy will be available.

It will be possible to simulate a flood disaster occurred at any areas in the world in detail if DEM with global coverage and high accuracy become available. Flood simulation is expected to support disaster mitigation activities of various organizations. Major users of flood simulation are;
(a) Local governments. The software can be used to evacuate citizens from areas where flooding may soon occur. If staff in the local government find that some sections of levees are about to fail, they can simulate what-if scenarios of the levee failure using the software.
(b) International rescue organization. The software can be used for preparing a rescue team. If staff members know a typhoon attacked an area and the area has just been flooded, they can simulate the scenario of the typhoon using the software and estimate the quantity of required supplies.
(c) Insurance companies. The software can be used to calculate insurance payments for insured houses. If staff members know their customers' properties have just been damaged by a flood caused by heavy rainfall, they can simulate the scenario of the rainfall using the software and estimate the amount of payment.

Our goal is to provide the global scale simulation software, which runs fast on a personal computer. The software simulates a flood disaster occurred at any areas where DEM is available. To develop the software, we found two of the major technical challenges:
(1) To retrieve data with best accuracy on global scale. Simulator requires accurate data, in particular, surface elevation. Although accurate surface elevations have been obtained in many major cities, it is still difficult to make an accurate dataset of the entire world surface.
(2) To define the simulation area in which any flood disasters can be simulated. In conventional method, we must define the simulation area in advance the simulation. The simulation is conducted only in the simulation area. The simulation area must include the flooded area. In general, we can not perfectly predict flooded area in advance the flood simulation.

We propose the following methods to overcome these technical challenges, respectively:
(1) To use geographical information system (GIS) which manages spatial data according to time, location, and accuracy. The architecture allows us to store multiple values with different accuracies, and to retrieve most accurate one in the stored data.
(2) To use the calculation method named Dynamic Domain Defining Method (DDM) developed by Yamaguchi and Iwamura (2007). In the Dynamic DDM, areas around a flooded area are automatically included in the simulation area, and the nonflooded areas are automatically excluded from the simulation area during the simulation. Data in the area which is newly included in the simulation area is automatically loaded from the GIS.

In this paper, we explain these methods in detail (section 2). Then, we evaluate the accuracy and computational time of the global flood simulation software (section 3). In section 4, we discuss the advantage of the methods. We conclude in section 5.

2. METHODS

2.1 Data management method for flood simulation

We developed GIS which can store/retrieve spatial data with wide coverage and high accuracy. The system uses earth-centered coordinates (spatial coordinates with their origin at the center of the earth), so it can represent any location on the earth. In addition, the GIS use five axes; space (x, y, z), time (t) and level of detail (LoD). Each value in the system has its own LoD information. The GIS stores/retrieves data with different accuracy as data with different LoD. In global view, we use data with global coverage (low LoD), and in local view, we use data with high accuracy (high LoD). This architecture allows us to store plural DEM data for one location, and load the most accurate DEM data in stored DEM data. As shown in Figure 1a, the globe is visualized because of the wide data coverage. As shown in Figure 1b, the GIS can visualize the local area with surface image and buildings because of the utilization of the LoD axis.

We stored DEM data in the GIS. The most accurate stored data is with 5-m horizontal resolution in the cities and in some areas along large rivers. DEM data with intermediate accuracy (50-m horizontal resolution), and rough accuracy (90-m horizontal resolution) are also stored in the system. The DEM data covers the entire land area on the earth. The system is shown to be able to store DEM data with any accuracy for any location on the earth.

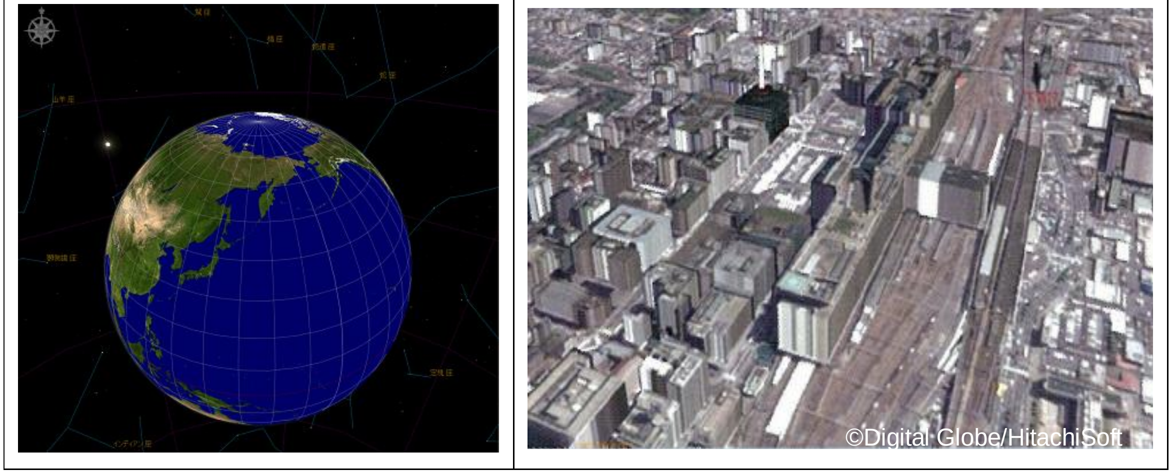
(a) Global view
(b) Local view
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Figure 1: Screenshots of our GIS software (a) global view with stars and the sun, (b) local view with three-dimensional shape of buildings.

Table 1: DEM data stored in system.
(NASA: National Aeronautics and Space Administration, GSI: Geographical Survey Institute)

Product name	Publisher	Coverage	Horizontal resolution	Vertical resolution
SRTM DEM	NASA, US	Entire land area on the earth	90 m	1 m
Digital Map 50-m	GSI, Japan	Entire land area in Japan	50 m	1 m
Digital Map 5-m	GSI, Japan	Major cities in Japan	5 m	0.1 m

2.2 Fast calculation method for flood simulation

For accurate flood simulation, numerical models based on two-dimensional shallow-water equations are commonly used. The accuracy of those models has been checked by comparing with site investigation data (e.g., Connell et al., 2001). The equations are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=q\ , \tag{1}$$

$$\frac{\partial (uh)}{\partial t}=-gh\frac{\partial H}{\partial x}-\frac{gn^2}{h^{4/3}}(uh)\sqrt{u^2+v^2}\ \text{, and} \tag{2}$$

$$\frac{\partial (vh)}{\partial t}=-gh\frac{\partial H}{\partial y}-\frac{gn^2}{h^{4/3}}(vh)\sqrt{u^2+v^2}\ , \tag{3}$$

where h = water depth; H = water level ($h+L$, L = ground level); u and v = velocity components in the x and y directions, respectively; g = gravitational acceleration; n = Manning's roughness coefficient; q = vertical inflow quantity.

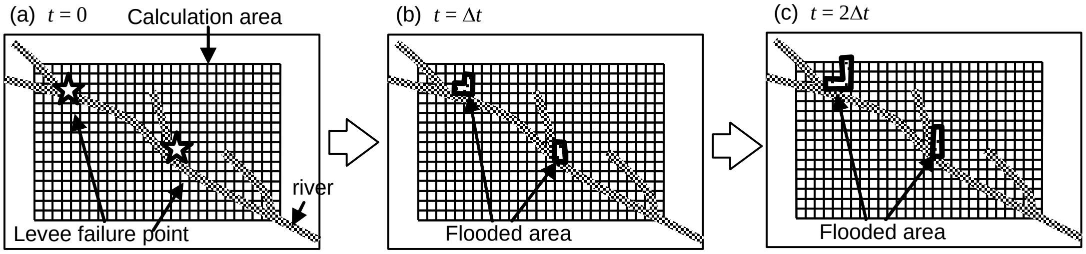


Figure 2: Calculation area in conventional method.

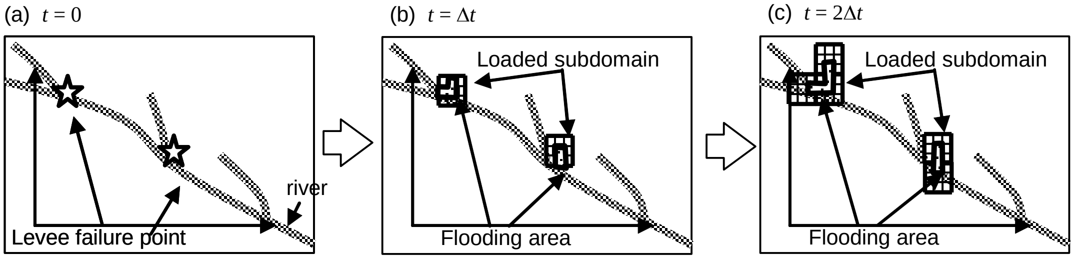


Figure 3: Calculation area in Dynamic DDM. Activated subdomains are calculation areas.

The numerical model is solved only in predefined area (simulation area). To control the simulation area, we developed the Dynamic DDM. The Dynamic DDM automatically defines its simulation area. We illustrate the difference between a conventional method and the Dynamic DDM in figures 2 and 3. As shown in Figure 2a, the simulation area must be defined in advance of the simulation in a conventional method. As shown in Figure 2b, the numerical model outputs the water state slightly after the time of Figure 2a (i.e., $t=\Delta t$). To repeat this process, the model outputs the water state slightly after the time of Figure 2b (i.e., $t=2\Delta t$), as shown in Figure 2c. The process is repeated more to simulate the later water state.

In a simulation area in the conventional method, there are many dry grids (grids in which there are no water). Of course, there is no need to simulate flooding at the dry grids. On the other hand, when the flooded area is reached the boundary of the simulation area, the simulated flooded area may be smaller, because the areas out of the simulation area cannot be simulated. We need simulation area with less dry grids and no boundary of the simulation area.

The Dynamic DDM automatically expands or shrinks the calculation area during the simulation. As shown in Figure 3a, a user inputs the levee failure point(s). Then, the entire area is divided into multiple subdomains which consist with multiple grids. Data in the subdomain(s) that include the levee failure point(s) are loaded into the computer memory (Figure 3b). The size of subdomain is 3 x 3 grids in the figure. The numerical model is calculated only in the loaded subdomains. When the water reaches a boundary of the loaded subdomains, the next subdomain will be loaded into the memory. On the other hand, when all the water in a subdomain has been drained away, the subdomain will be unloaded from the memory. Thus, the Dynamic DDM automatically defines its calculation area and reduces the computation time.

3. EXPERIMENT AND RESULTS

We checked the accuracy of the flood simulation result by comparing a site investigation data. We simulated the flood disaster occurred in Fukui City, Japan, in 2004. The flood occurred in a densely populated city area, in which many man-made structures such as buildings, houses, roads, and banks of railway tracks exist (Yamaguchi and Iwamura, 2006). The major cause of the flood was a levee failure with 54-m long that occurred at about 12 noon on July 18, 2004. The flooded area continued to spread for about 6 hours until the failure point was repaired. The maximum flooded area was 260 hectares. About 2,740 houses were flooded above floor level, and about 4,100 houses were flooded below floor level.

The site investigation was conducted by Yamamoto (2005). He estimated the flooded area based on the site investigation, interviews of residents, and aerial photographs that were taken immediately after the flood. He also measured the flood water level at 146 points in the city from July 21 (3 days after the flood occurred) to July 29. He measured the height of a mud trace on vertical faces such as a tree trunk, house wall, and guardrail using a non-prism laser range finder from a point at which the elevation is already known. Mud traces indicated the maximum water level in the flood. Elevations at many points had already been measured by the local government for city planning. Then, he calculated the water level by adding the elevation of the measured point to the height of the mud trace. Errors in measuring the water level were caused by the measurements of the height of mud traces (estimated error is ±3 cm) and measurements of the elevation of the points (estimated error is ±10 cm).

For the experiment, we used a square grid with intervals of 10, 25, 50, 100, 150, and 300 m. Elevation of each grid is created by re-sampling from DEM data which is stored in the GIS. The resolution of the original DEM is 5-m horizontal and 0.1-m vertical.

The comparison between the simulation result and the site investigation of the flooded area is shown in Figure 4. By the simulation on 10-m grids, the simulated flooded area covered 91% of the actual flooded area, and the actual flooded area included 87% of the simulated flooded area. The root-mean-square error of the simulated water level was 28 cm for the 146 points. By the simulation on 100-, 150-, and 300-grids, the accuracy decreased significantly because features of key structures at the disaster (e.g., a bank of a railway and a culvert) could not be reproduced. Therefore, we found that a 50-m or smaller grid is needed for accurate simulation in this densely populated city.

To confirm the efficiency of Dynamic DDM, we measured the computation time. The specification of the used a laptop computer is shown in Table 2. The simulated disaster was the same as that in the validation study. During the simulation, simulated water depth was displayed on the screen and updated every 10 minutes in the simulation time.

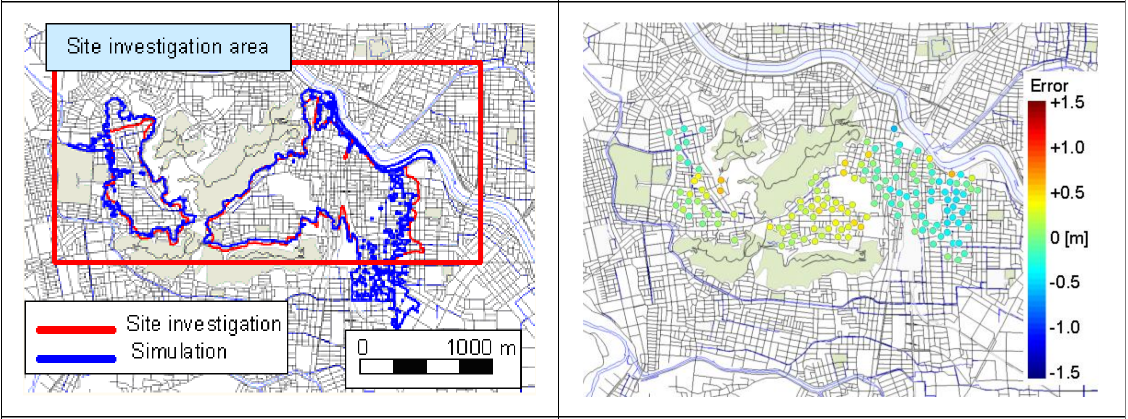
In the simulation on 10-m (25-m) grids, the computation time for a 3-hour simulation is 5 minutes 49 seconds (22 seconds) on the computer, and that for a 6.5-hour simulation is 26 minutes 49 seconds (2 minutes 16 seconds). Though the finer grid resulted in a higher accuracy with a longer computational time, the computational times with both 10-m and 25-m grids are acceptable for practical use.

Table 2: Specifications of laptop computer for measuring performance.

Type	IBM T43P
Manufactured year	2005
CPU	Intel® Pentium® M Processor 2.13 GHz
OS	Microsoft® Windows® XP Professional
Memory	1024 MB
Graphic board	ATI Mobility FireGL V3200

(a) Error in flood area (map view)

(b) Error in flood water level (map view)



(c) Error rate in flood area

(d) Error rate in flood water level

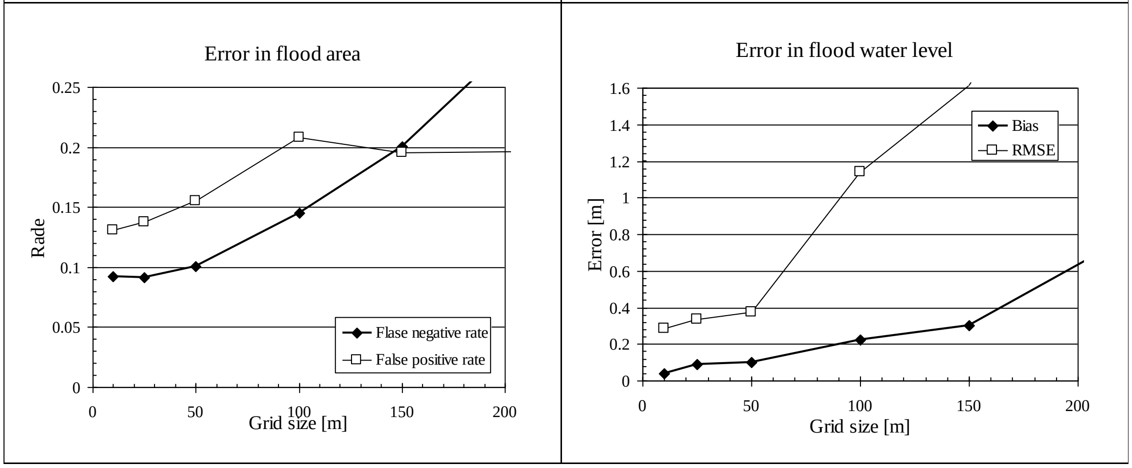


Figure 4: Comparison between simulation result and site investigation of flooded area. Data of the site investigation is based on Yamamoto (2005). (a) and (b) is simulated on10-m grids.

4. DISCUSSION

Developed software can simulate flood disaster in many areas in a short computational time. At present, the software can simulate a flood disaster in major Japanese cities with 5-m horizontal resolution terrain data, in the entire area of Japan with 50-m horizontal resolution terrain data, and in the entire land area on the earth with 90-m horizontal resolution terrain data. A simulation result of Fukui flood disaster adequately corresponds with a site investigation, and computational time for the simulation is less than 30 minutes in a laptop computer. As the next step, we need more validation of the simulation results and case studies of the use of the software.

In addition, the software provides good user interface as shown in Figure 5. The simulation result can be visualized as a three-dimensional map during the simulation. Red allows indicates failed levee. User can specify the location of failed levee just by mouse clicking on the levee in the map. Because of this convenience, specialists in various fields can use the software easily. Yamaguchi et al. (2007) reported that a use case of the software in insurance industry. In that case, the users of the software are risk consultants, and they can easily generate time series data of water depth and flow speed in various flood disaster scenarios. Thus, this detailed information assists to assess flood risks quantitatively.

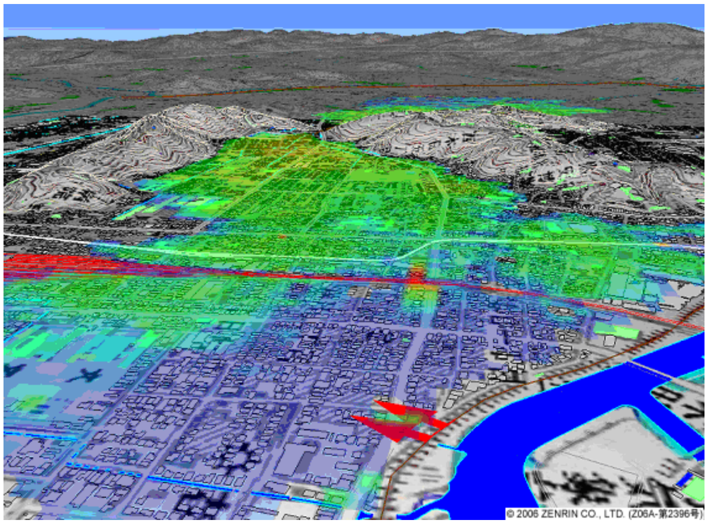


Figure 5: Enlarged graphics near the levee failure point indicated by red arrows. Simulated water depths are also shown (blue = 1 cm, green = 1 m, red = 4 m). Shapes of houses are indicated by black rectangles.

5. CONCLUSION

To develop flood simulation software that immediately simulate a flood disasters in any areas where we have DEM data, we overcome two major technical challenges;
(1) To prepare data with global coverage and best accuracy.
(2) To define the simulation area in which any flood disasters can be simulated.

To overcome the two challenges, we propose the following methods, respectively;
(1) To use geographical information system (GIS) which manages a value according to time, location, and accuracy.
(2) To use the calculation method named Dynamic Domain Defining Method (DDM).

To evaluate the accuracy and the computational time of the simulation, an actual flood disaster that occurred in Fukui in 2004 was simulated using the software. Using accurate DEM data with a 10-m grid, an accurate result (RMSE of water depth is 28 cm) was computed in a short time (26minutes 49 sec).

The software has capability to simulate flood disaster scenarios in many areas in a short computational time. Because of this convenience, users without detailed hydraulic knowledge use the software.

At present, accurate data is available in a limited area. More validation of the simulation results are expected. In the near future, accurate data will be available in many areas. To contribute more for disaster mitigation, we need more case studies of the use the software.

6. ACKNOWLEDGEMENTS

The authors are grateful to the following organizations for providing map data: Geographical Survey Institute of Japan (5-m and 50-m horizontal resolution digital elevation data (product name: Digital Map 5-m Grid Elevation and Digital Map 50-m Grid Elevation), and 1:25,000 scale map images (product name: Digital Map 25000 Map Image) with its approval (approval number: SOU-SHI No.635 2005) under the article 30 of The Survey Act); Kinki Regional Development Bureau, Ministry of Land, Infrastructure and Transport (5-m horizontal resolution digital elevation data in Fukui City); Zenrin Co. Ltd. (house map (product name: Zmap-TownII) with its approval (approval number: Z06A-2396)); CAD Center Corporation (Landmark building data (product name: MAPCUBE3D digital map)); DigitalGlobe/Hitachi Software engineering Co Ltd. (Satellite images); NASA’s Earth Observatory (global terrain data and satellite images (product name: Blue Marble Next Generation)).

The authors used the commercial geographical information system (product name: DioVISTA) and its extension (product name: DioVISTA/FloodSimulator version 2.0) produced by Hitachi Engineering & Services Co., Ltd.

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