Development of GIS-Based Flood-Simulation Software and Application to Flood-Risk Assessment

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Abstract

We developed flood simulation software, which works with geographic information systems, and applied the software to a flood-risk assessment of a commercial facility. The developed software provides an easy-to-use user interface, and rapidly and accurately simulates flood scenarios. Using the software, we assess risks at a facility of an entertainment complex. The facility is located on a flat plain surrounded by two rivers. Based on site investigations, three possible flood scenarios were considered. The simulations using the software revealed the most dangerous scenario; if a levee fails at the nearest river, then the water depth in the facility will be greater than 15 cm in just 10 minutes, and the water depth would rise to 50 cm in 1 hour. Water current speed would exceed 2 m/sec, in which even an adult cannot walk. Based on these findings, a recommendation can be made to evacuate the ground floor, and for the guests to move to upper floors. Because the developed software enables risk consultants to consider countermeasures based on realistic flood-disaster scenarios, we conclude that the software is suitable for effectively assessing flood risk.

1. Introduction

Private companies have not assessed their flood risk well compared to governmental organization (Webb et al, 2001, Yoshida & Deyle, 2005). Recent expansion of interest in business continuity planning (BCP) indicates that private companies need to assess their own risk, and they need advice on how to prepare for and react to disasters. BCP should be based on realistic scenarios of flood disasters. Since flood simulations can reproduce information on water depth and water current speed from moment to moment in the disaster, flood simulation software can be a good tool for BCP consulting.

However, few risk consultants have used such simulation software. We estimate the reason is that the efforts required to obtain a simulation result are too great. Those efforts are: (1) to estimate the flooded area in advance of the simulation and to define a calculation area that is larger than the flooded area, (2) to acquire topographic data in the calculation area, and (3) to wait a long time until the calculation of the simulation is finished. The simulated flood area will be not correct when the simulated water flow reaches the edge of the calculation area. To prevent this failure, users tend to define a significantly larger calculation area, which makes the computation time much longer.

The purpose of this study is to provide software that is useful for risk consulting. To lessen the aforesaid user burdens, the software should (1) automatically define the calculation area, (2) automatically acquire topographic data, and (3) rapidly output the result. To achieve functions (1) and (3), we use a calculation method called the dynamic domain defining method (Dynamic DDM). To achieve function (2), we integrate the simulation and commercial geographical information system (GIS) called Hitachi DioVISTA. Then, to check the usefulness of the software, we use the software for risk consulting. Based on the use case, we make a conclusion.

2. Development of Flood Simulation Software

2.1 Numerical flood model and its accuracy

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

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

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

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

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.

We already have validated our model, which uses a discrete form of the shallow water equations (Yamaguchi & Iwamura, 2007). We compared the simulation result with a site investigation of the flood disaster that occurred in Fukui City, Japan, in 2004. The major cause of the flood was a levee failure for 54-m which occurred at about 12 noon on July 18, 2004, and 220 hectares of a residential area were flooded. The flooded area continued to spread for about 6 hours until the failure point was fixed. The comparison between the simulation result and the site investigation of the flooded area is shown in Figure 1. In the simulation we used a square grid with intervals of 10 m. 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. The water depth was compared at 146 points where the water depth were measured in the site investigation. The accuracy of this validation study is sufficient for the risk assessment.

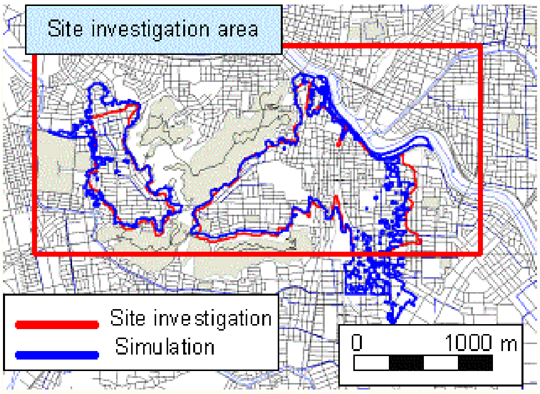


FIGURE 1. Comparison between simulation result and site investigation of flooded area. The data of the site investigation is based on Yamamoto (2005).

2.2 Calculation method of model

To implement the numerical model with the function that automatically defines the calculation area and rapidly outputs the results, we adopt the Dynamic DDM (Yamaguchi & Iwamura, 2007). The Dynamic DDM automatically defines its calculation area to reduce the computation time.

We illustrate the difference between a conventional method and the Dynamic DDM using figures. As shown in Figure 2a, a conventional method requires the user to define the calculation area in advance of the simulation. As shown in Figure 2b, the numerical model outputs the water state slightly after the time of Figure 2a. To repeat this process, the model outputs the water state slightly after the time of Figure 2b, as shown in Figure 2c. In addition, the process can be used to simulate the water state after the time of Figure 2c. In a calculation area of the conventional method, however, you will find many dry grid cells with no flooding. Of course, there is no need to simulate flooding at dry grid cells.

The Dynamic DDM automatically expands or shrinks the calculation area during the simulation to exclude dry grid cells. In advance of the simulation, the entire area is divided into multiple subdomains. As shown in Figure 3a, a user inputs the levee failure point(s). Then, data in the subdomain(s) that include the levee failure point(s) are loaded into the computer memory (Figure 2b). The numerical model is calculated only in the loaded subdomains. If the water reaches an edge of the loaded subdomains, the next subdomain will be loaded. On the other hand, if all the water in a subdomain has been drained away, the subdomain will be unload from the memory. Thus, the Dynamic DDM automatically defines its calculation area and reduces the computation time.

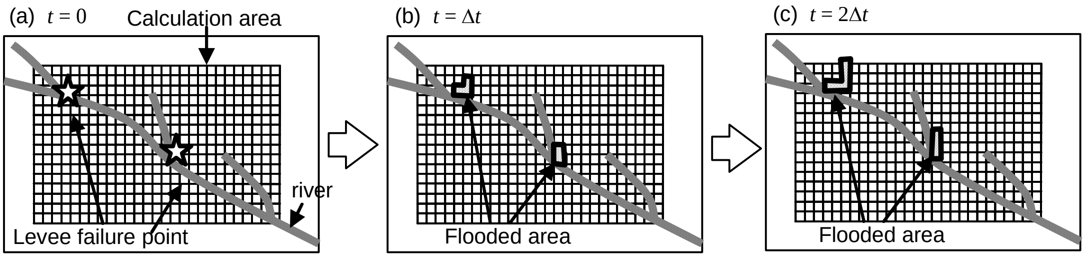


FIGURE 2. Calculation area in conventional method.

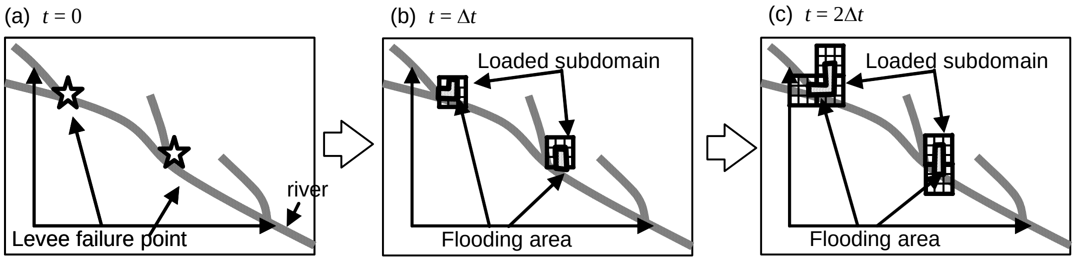


FIGURE 3. Calculation area in Dynamic DDM. Activated subdomains are calculation area.

2.3 Integration of model and GIS

To implement the model with the function that automatically acquires topographic data, we used the commercial GIS called Hitachi DioVISTA developed by Hitachi Engineering & Services Co. Ltd. As shown in Figure 4, Hitachi DioVISTA manages spatial information globally and locally, and visualizes them in three dimensions.

We input global and local topographic data shown in Table 1 into the GIS. The topographic data of the Digital Map (5 m) has the same accuracy as that of the validation study performed in Fukui. Because the accuracies of the simulation result in the sites with the topographic data are expected to be the same as those of the validation study, the accuracy is expected to be sufficient for the risk assessment. This data was obtained by an airborne laser scanning, and an increasing number of cities in Japan are measured by the method. So, this software is expected to output accurate simulation result in major cities in Japan.

We integrated the model and GIS. Screen shots of the software are shown in Figures 5 and 6. As shown in Figure 5, a user can input levee failure points on the three-dimensional map. Red arrows perpendicular to the levee indicate the flow direction of the outflow. In addition, a simulation result is also shown on the same map. The blue-green gradation indicates the water depth of flooding. As shown in Figure 6, the software integrates the water surface and buildings three-dimensionally. Such graphics help a user to estimate property damage in a disaster.

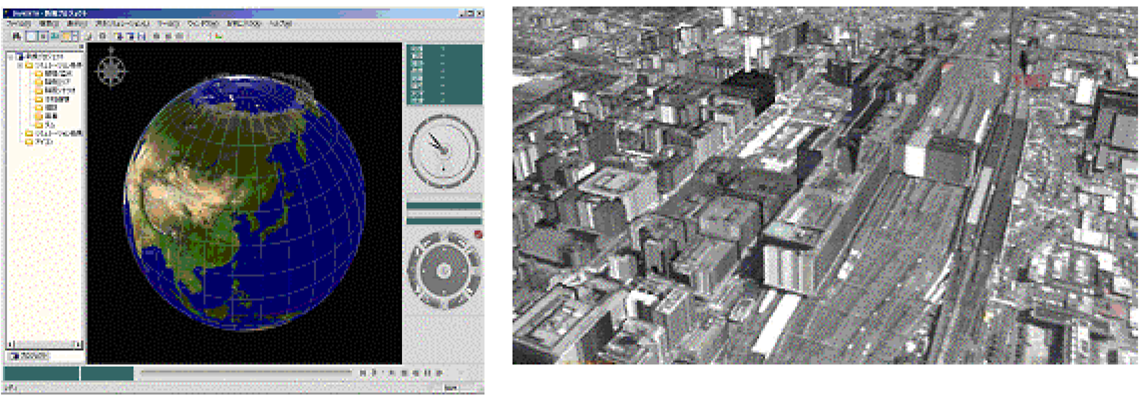


FIGURE 4. Screen shots of Hitachi DioVISTA. Global view (left) and local view (right).

TABLE 1. Digital elevation data used in simulation

Data source	Author	Covered area	Resolution (horizontal/vertical)
SRTM	NASA, US	Global	90 m/1 m
Digital Map 50 m	GSI, Japan	Whole of Japan	50 m/1 m
Digital Map 5 m	GSI, Japan	Major cities in Japan (eg., Tokyo, Osaka, Kyoto)	5 m /0.1 m

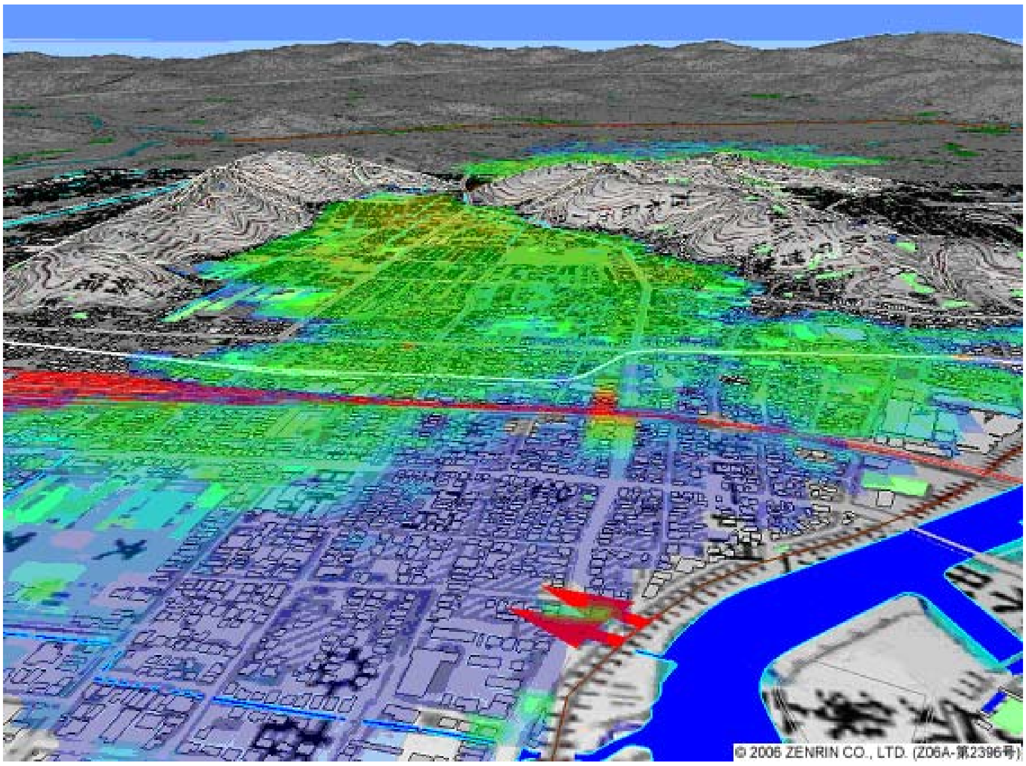


FIGURE 5. Enlarged graphics near the levee failure point indicated by red arrows. Simulated water depths are also shown (blue = 1 cm, green = 1 m, red = 4 m).

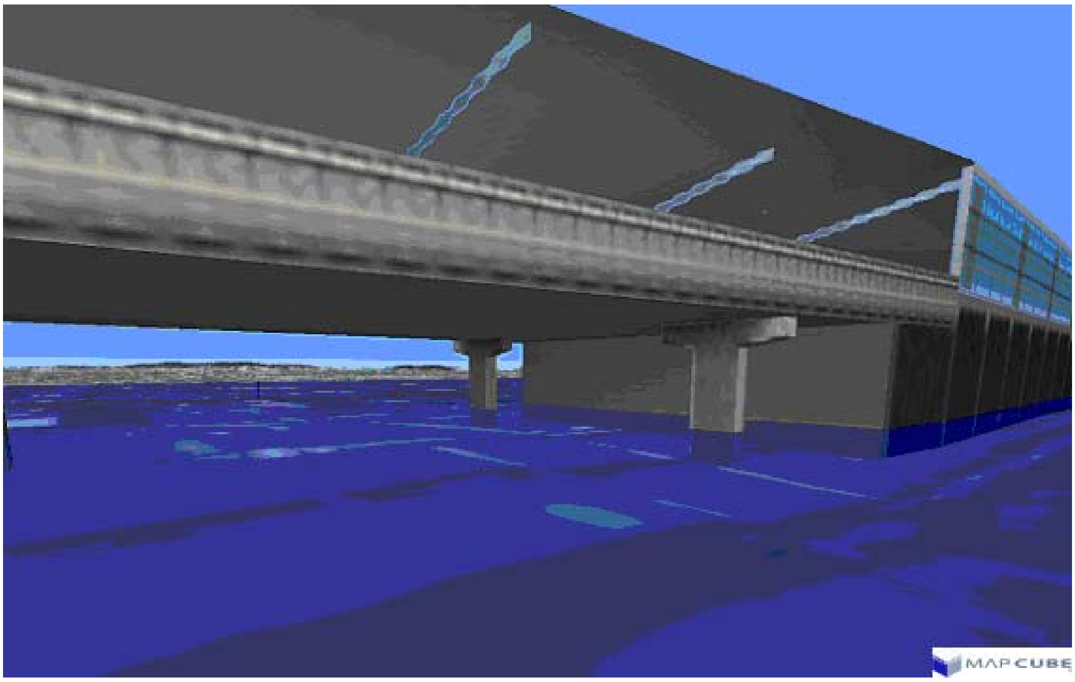


FIGURE 6. Integrated graphics of water surface and a train station with elevated railway.

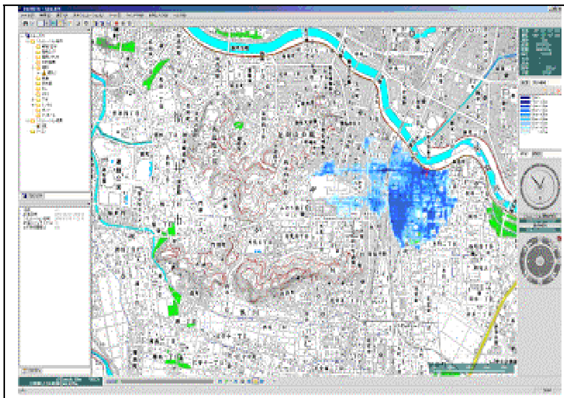
2.4 Rapidity of software

To check the rapidity of the software, we measured the computation time. Because we want to check that our software does not require latest computers, we used a 2-year-old laptop computer to measure the computation time. The specification of the laptop is shown in Table 2. Simulated disaster was same as that in the validation study. Water state from the levee failure to 6 hours later was simulated with the 10-m-square grids. During the simulation, water depth at every 10 minutes was displayed on the screen as shown in Figure 7. Additionally, simulated water depth and water current speed at every 10 minutes were saved to a file.

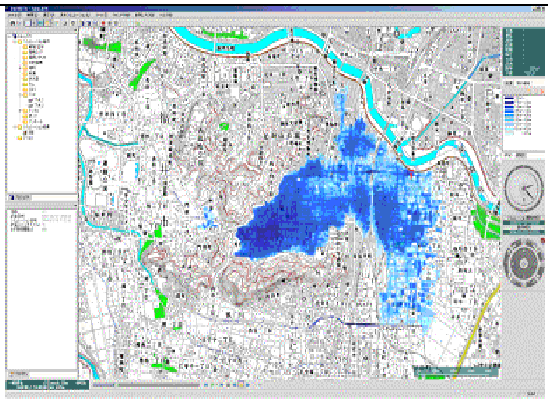
The result is shown in Figure 7. The computation time for 3 hours was 8 minutes 14 second, and for 6 hours was 27 minutes 21 second. The computation time is acceptable for the purpose of risk consulting.

TABLE 2. Specifications of laptop computer for measuring performance.

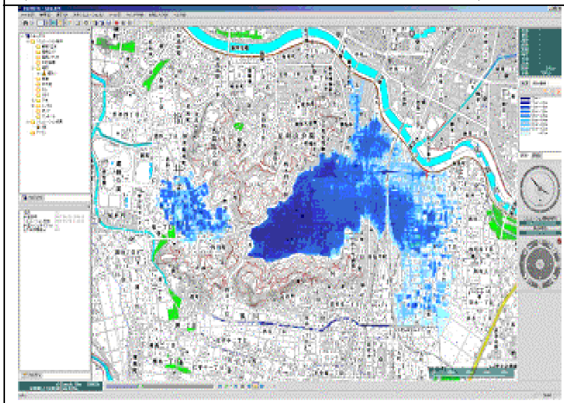
Type	Dell Precision M70
Manufactured year	2005
CPU	Intel® Pentium® M Processor 1.86 GHz
OS	Microsoft® Windows® XP Professional
Memory	1024 MB DDR2 SDRAM Memory
Graphic board	NVIDIA Quadro® FX Go1400



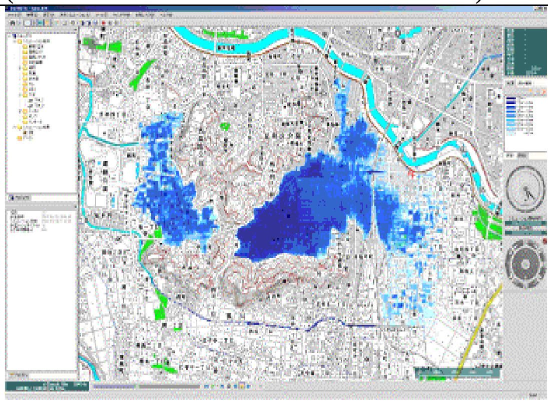
1.5 hours after levee failure
(1 minute 54 seconds after calculation start)



3 hours after levee failure
(8 minutes 14 seconds after calculation start)



4.5 hours after levee failure
(17 minutes 11 seconds after calculation start)



6 hours after levee failure
(27 minutes 21 seconds after calculation start)

FIGURE 7. Simulated result and computational time required by laptop computer shown in Table 2.

3. Application to Flood Risk Assessment

3.1 Assessed facility

We applied the simulation software to a flood-risk assessment of an entertainment complex-facility of a private company in Japan. As shown in Table 3, the facility offers several kinds of indoor entertainment such as movies. The facility is located in a mixed residential and industrial area in the suburbs.

There are two rivers near the facility . The River A is about 120 m wide, and the River B is about 60 m wide. Because the distance from the site to the coastline is about 5 km and the ground level of the site is just slightly higher than the high tide level, the water levels of the rivers are affected by the tide level at the river mouths. There are frequent occurrences of flood around the facility. The latest flood occurred in September 2000 due to heavy rainfall. According to the flood-risk assessment performed by the local government, if rainfall with a return period of 200 years (250 mm/day) occurs and the levee of the river fails, the water depth around the facility would reach 2 m. However, there is no information on the possible situation in other scenarios such as a rainfall with a shorter return period, overflowing from the rivers, or levee failures at other locations.

TABLE 3. Assessed facility

Location	Floodplain bounded by River A and River B. About 5 km distance form the coastline. Located in mixed residential and industrial area in the suburb.
Use	Entertainment complex
Constructions	Main building, Building No. 2, parking garage

3.2 Considered scenarios

Based on interviews with the waterways bureau, literature on past floods, and site investigation of current land use and levee's present condition, three possible flood scenarios were considered: A) failure of the River A levee, B) overflow at the curve of River B, and C) the heaviest rainfall ever recorded in the area. These scenarios are shown in Table 4.

TABLE 4. Considered scenarios

Scenario	Description
A	Levee failure at River A. The levee is build of reinforced concrete, but some part of the parapet on the levee near the facility have been weakened. It is thus assumed that the levee itself would withstand an overflowing, but the parapet would fail. As the height of the parapet is 0.5 m, the failure height was set at 0.5 m. Based on the location and length of the weakened portion, failure location was assumed to be near the facility, and the failure length was set at 30 m.
B	Overflowing at River B. Because River B bends near the facility and levees are not constructed at the curve, overflowing may occur at the curve. Based on the location of the curve and width of the river at that location, the overflow location was assumed to be near the curve and the length of overflow section was set at 50 m. Based on the high tide level at the river mouth, the water level at overflows point was set at 1 m higher than the top of the river bank.
C	Heavy rainfall (97 mm/hr) The heaviest rainfall was determined from the weather records for the vicinity around the facility from 1981 to 2005. It was assumed that the rainfall would last for 1 hour.

4. Results

We assessed the facility's flood risk according to Scenarios A, B, and C. The situation in and around the facility differs dramatically among these scenarios. The facility would suffer major damage in Scenario A, while there would be no significant damage in Scenarios B and C.

The advisory for people in Scenario A is as follows: the water level in and around the facility would rise rapidly. The water depth in the facility would exceed 15 cm in just 10 minutes and would reach 50 cm in 60 minutes after levee failure. In addition, water current speed would exceed 2 m/sec, in which even an adult cannot walk. Based on these findings, it is recommended that the ground floor be evacuated, and guests be moved to upper floors in a quick, efficient manner. In addition, staff should be trained to undertake the evacuation procedures.

The advisory about the property in Scenario A is as follows: the maximum water depth in the facility would be 50 cm. Properties such as commercial goods, store furniture, interiors, power and water supply facilities, sewage facilities, air conditioning facilities, and elevators would be damaged. Based on these findings, it is recommended that a flood proofing system such as floodwall over 50 cm high be installed to mitigate the damage.

The advisory in Scenarios B and C is as follows: there would be no significant damage in the facility. However, roads and some part of residential area would be flooded. Guests in the facility would be unable to go home. In addition, neighbours may rush to the facility to escape from the flooding. Based on these findings, it is recommended that the facility be designed to offer a temporary shelter for both guests and neighbours. In addition, staff should be trained to provide current flood situation information for the guests.

TABLE 5. Damage and countermeasures in each scenario

Scenario	Damage	Counter measures
A	Maximum water depth in the facility would be 50 cm 60 minutes after levee failure. The ground floor would be flooded. Almost all equipment on the floor would be damaged.	Guests should be evacuated to upper floors. Staff should indicate evacuation routes to guests. A flood proofing system such as floodwall with over 50 cm high should be installed.
B	No significant damage in the facility. At roads near the facility and in some part of residential area near River B, the water level would reach 50 - 150 cm. A traffic jam would occur and neighbours may rush to the facility to escape from the flooding.	The facility should offer a temporary shelter for both guests and neighbours. Staff should provide current flood situation information for guests.
C	No significant damage in the facility. Heavy rain would cause a traffic jam at roads near the facility. In some part of residential area near the facility, the water level would exceed 15 cm. Neighbours may rush to the facility to escape from flooding.	The facility should offer a temporary shelter for both guests and some neighbours. Staff should provide current flood situation information for guests.

5. Conclusion

We conclude that:

1. The developed software enables risk consultants to simulate flooding because of the three functions: (1) automatic definition of the calculation area, (2) automatic acquisition of topographic data, and (3) rapid output of the result.
2. The information generated by the developed software enables risk consultants to precisely assess the risks and to develop measures against them. The simulation software provides water depth, current speed, and visual information such as three-dimensional computer graphics of the assessed facility.

Acknowledgements

In this article, we use the following map contents: Digital Map 25000 (Map Image), Digital Map 50-m Grid (Elevation), and Digital Map 5-m Grid (Elevation) published by the Geographical Survey Institute, Japan with its approval under article 30 of The Survey Act (Approval No. SOU-SHI No.635 2005). In addition, we use the Housing Map “Zmap-Town II” published by Zenrin Co, Ltd. (Approval No. Z06A-2396), the dataset of the NASA Earth Observatory Global Land Cover Facility, satellite images published by Digital Globe/Hitachi Software Engineering Co. Ltd., and landmark-shape data published by CAD Center Corporation.

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