Floods, from Defence to Management – Van Alphen, van Beek & Taal (eds)

Flood risk analysis toward floodplain risk management

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ABSTRACT: Active seasonal rain fronts and a lot of typhoons in 2004 brought heavy rain and flood in Japan. This paper discusses the background of increasing damage based on those examples. Severe flood damage due to the dyke break occurred in Niigata Prefecture. Especially many houses were broken and many people failed to evacuate from inundated area in Nakanoshima area along Kariyata River. Numerical analysis for flood flow is useful to manage floodplain risk. General flood simulation is presently being used to predict flooding water depth and to make hazard map for evacuation of people in river basin etc. Objects of the general numerical analysis are not to predict damage due to abrupt flooding flow near dyke break point. We developed a new numerical analysis model by FDS (Flux Difference Splitting) method for abrupt flooding flow and swept-away of houses. We made clear the relationship between the flood flow from the Kariyata River and swept-away of houses due to dyke break using the numerical model.

1 INTRODUCTION

Generally, it is said that structural and non-structural measures are needed to mitigate flood damage. Structural measures are performed by dyke, dam and flood-diversion channel etc. Non-structural measures are taken through planning for evacuation and flood protection as well as publication of a hazard map. Flood simulation became important for floodplain risk management.

In this paper we discusses the flood damage that occurred in Japan during the year 2004 and we tried to make some improvements on new simulation technique by FDS method to estimate flood risk with dyke break of Kariyata River.

2 FLOOD RISK IN JAPAN AND FLOOD DAMAGE IN 2004

2.1 *Weather condition and excess flood*

During the year 2004, seasonal rain fronts were so active and many typhoons hit Japan. We had about 470 times of heavy rain with more than 50 mm/hour in that year only. This can be said tremendous since we had only 271 times of heavy rain like that from 1996 to 2003 in annual average.

Excess flood beyond improved dyke arose in various places in 2004. Except for the cases of some large rivers with high graded dyke, there are only few examples in which the measure are taken for the excess flood, and that has been causing serious damages in the area people and property accumulated along river.

2.2 *Flood damage*

Many houses were destroyed completely or partially by heavy rain along with seasonal rain front in Niigata and Fukushima pref. in July 2004 and typhoon No.18. More than 50,000 houses were damaged by typhoon No.16, 18 and 23. Dyke breaks occurred at 6 point by the excess flood of Kariyata River in Niigata. The flood probability is estimated to be 1/150. The amount of the damage from storm and flood reached 1.2 trillion yen only by immediate damage related to public infrastructures of the road and farm products, etc. The number of missing and dead from the storm and flood damage reached 227, which is the largest numbers since 1984. Among 194 people of age available, 119 were senior citizen of 65 years old or more. There was seen a feature that death risk of senior citizen was high.

2.3 *Background of damage increase*

As already stated, the scale of heavy rain and wind brought by the active seasonal rain front and a lot of typhoons was big and has never experience before.

Except for weather condition, the possible causes of increasing flood damages are as follows.

1. Insufficient improvements of small and middle rivers
2. Accumulation of population and property along small and middle rivers
3. Increases of handicapped persons who need to help in flood time
4. Communication gap of information for evacuation
5. Shortage of assistance by local community
6. Untapped experience in the past flood disaster
7. Frequent occurrence of excess flood.

Big damage, which 3 persons were dead and 16 houses swept away etc., be brought about by large part of above-mentioned background in the flood of Nakanoshima area along Kariyata River. A lot of person did not evacuate due to rapid water rise by flooding with dyke break. Numerical analysis to predict flood flow can be helped to evacuation and moreover it is useful to manage floodplain risk.

3 EXISTING STUDY ON FLOOD SIMULATION

Iwasa and Inoue et al. developed 2-dimensional unsteady flood flow simulation model to analysis for Yodo River etc. Kuriki and Suetsugi et al. developed general flood simulation model introduced force by houses as roughness coefficient. However the general flood simulation model is used to predict flooding water depth and to make hazard map for evacuation of people in river basin etc. In the simulation model, formula of overflow discharge from river was used. Objects of the general numerical analysis are not to predict damage due to abrupt flooding flow near dyke break point.

Fukuoka and Kawashima et al. developed 2-dimensional shallow water model on general coordinate system for urban residential area. It made clear that hydrodynamic force acting on non-submerged houses is represented by difference of pressure on upstream and downstream side of house assuming as hydrostatic pressure and that flood flow and hydrodynamic force is represented with good accuracy by modeling road and houses adequately.

Akiyama and Shigeeda et al. developed 2-dimensional shallow water model by FDS method. Temporal profile of experimental flood flow and hydrodynamic force by unsteady flow was represented with good accuracy.

We developed new 2-dimensional flood simulation model by FDS method to represent flood flow in river channel, abrupt flooding flow in floodplain and swept-away of houses for floodplain risk management.

4 FLOOD SIMULATION DUE TO DYKE BREAK BY FDS METHOD

4.1 *Basic equation*

Basic equation for flood flow simulation is 2-dimensional shallow water equation of conservative form. The basic equation is discritized by FDS (Flux Difference Splitting) method as follows. Because importance of the simulation is to represent advective current on river channel and floodplain around broken dyke, it is thought that diffusion term is smaller than the other terms. Then, the basic equation is the following with the use of conservative vector $\boldsymbol{U}$, flux vector $\boldsymbol{E}$ on x axis, flux vector $\boldsymbol{F}$ on y axis and source term from gravity and friction on earth $\boldsymbol{S}$.

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{E}}{\partial x} + \frac{\partial \boldsymbol{F}}{\partial y} + \boldsymbol{S} = 0 \quad (1)$$

$$\boldsymbol{U} = (h \quad uh \quad vh)^T$$

$$\boldsymbol{E} = (uh \quad u^2 h + gh^2/2 \quad uvh)^T$$

$$\boldsymbol{F} = (vh \quad uvh \quad v^2 h + gh^2/2)^T$$

$$\boldsymbol{S} = \left(0 \quad gh\left(\frac{\partial z_b}{\partial x} - \frac{n^2 u\sqrt{u^2+v^2}}{h^{4/3}}\right) \quad gh\left(\frac{\partial z_b}{\partial y} - \frac{n^2 v\sqrt{u^2+v^2}}{h^{4/3}}\right)\right)$$

where h is water depth, u and v is velocity, g is gravity, z_b is elevation of the earth, n is Manning's roughness coefficient.

The basic equation is transformed to hyperbolic partial differential equation with use of characteristic velocity vector to make fluctuation frame clear, because the flood simulation aims at advective flood flow near dyke break point. Equation (1) can be transformed to hyperbolic equation with Jacobian of Flux $\boldsymbol{E}$ and $\boldsymbol{F}$.

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{J}_x \frac{\partial \boldsymbol{U}}{\partial x} + \boldsymbol{J}_y \frac{\partial \boldsymbol{U}}{\partial y} + \boldsymbol{S} = 0 \quad (2)$$

$$\boldsymbol{J}_x = \begin{pmatrix} 0 & 1 & 0 \\ -u^2+c^2 & 2u & 0 \\ -uv & v & u \end{pmatrix}, \quad \boldsymbol{J}_y = \begin{pmatrix} 0 & 0 & 1 \\ -uv & v & u \\ -v^2+c^2 & 0 & 2v \end{pmatrix}$$

where $\boldsymbol{J}_x = \partial \boldsymbol{E}/\partial \boldsymbol{U}$, $\boldsymbol{J}_y = \partial \boldsymbol{F}/\partial \boldsymbol{U}$ and c(= $\sqrt{gh}$ is wave speed.

Using right eigen vector $\boldsymbol{e}_x$ and $\boldsymbol{e}_y$, the equation (2) is the following equation with characteristic velocity vector λ_x, λ_y.

$$\frac{\partial \boldsymbol{U}}{\partial t} + (\boldsymbol{e}_x \boldsymbol{\lambda}_x \boldsymbol{e}_x^{-1})\frac{\partial \boldsymbol{U}}{\partial x} + (\boldsymbol{e}_y \boldsymbol{\lambda}_y \boldsymbol{e}_y^{-1})\frac{\partial \boldsymbol{U}}{\partial y} + \boldsymbol{S} = 0 \quad (3)$$

$$\boldsymbol{\lambda}_x = \boldsymbol{e}_x^{-1}\boldsymbol{J}_x\boldsymbol{e}_x \quad , \quad \boldsymbol{\lambda}_y = \boldsymbol{e}_y^{-1}\boldsymbol{J}_y\boldsymbol{e}_y$$

$$\boldsymbol{e}_x = \begin{pmatrix} 1 & 0 & 1 \\ u+c & 0 & u-c \\ v & c & v \end{pmatrix}, \quad \boldsymbol{e}_y = \begin{pmatrix} 1 & 0 & 1 \\ u & -c & u \\ v+c & 0 & v-c \end{pmatrix}$$

$$\boldsymbol{\lambda}_x = \begin{pmatrix} u+c & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & u-c \end{pmatrix}, \quad \boldsymbol{\lambda}_y = \begin{pmatrix} v+c & 0 & 0 \\ 0 & v & 0 \\ 0 & 0 & v-c \end{pmatrix}$$

The equation (3) means that partial differentiation $\partial\omega_x(=e^{-1}_x\partial \boldsymbol{U})$ and $\partial\omega_y(=\boldsymbol{e}^{-1}_x\partial \boldsymbol{U})$ are replaced to original space after the partial differentiation is transported by the characteristic velocity. Equation (4) discritized from equation (3) by finite difference method in next section is equal to discritized equation from integration of equation (3) by finite volume method. Transportation by multi-dimensional characteristic wave is not calculated in this basic equation for the flood flow simulation strictly. But it is thought that accuracy of this simulation is enough to predict risk of swept-away of houses by hydrodynamic force, because of comparison of experimental and numerical results in existing study.

4.2 *Discretization*

$\boldsymbol{F_x}$ and $\boldsymbol{F_y}$, which are numerical flux across cell interface, are estimated due to discritization of basic equation by finite volume method in Cartesian coordinate system.

$$\boldsymbol{U}^{n+1}_{(i,j)} = \boldsymbol{U}^{n}_{(i,j)} - \Delta t \left\{ \begin{aligned} &\left(\boldsymbol{F}_{x(i+1/2,j)} - \boldsymbol{F}_{x(i-1/2,j)}\right)/\Delta x \\ +&\left(\boldsymbol{F}_{y(i,j+1/2)} - \boldsymbol{F}_{y(i,j-1/2)}\right)/\Delta y + \boldsymbol{S}_{(i,j)} \end{aligned} \right\} \tag{4}$$

Flood flow around broken dyke is mixed subcritical and supercritical flow. So freezing Jacocian $\boldsymbol{J}_x$ and $\boldsymbol{J}_y$ locally is needed to assure physical conservation in area where physical discontinuous jump exists between calculate points. That is $\partial \boldsymbol{E} = \tilde{\boldsymbol{J}}_x\partial \boldsymbol{U}$ and $\partial \boldsymbol{F} = \tilde{\boldsymbol{J}}_x\partial \boldsymbol{U}$. Roe's velocity and wave speed is used to calculate characteristic velocity, right and left eigen vector on cell interface.

$$\tilde{u} = \frac{\sqrt{h_L}u_L + \sqrt{h_R}u_R}{\sqrt{h_L} + \sqrt{h_R}}, \; \tilde{v} = \frac{\sqrt{h_L}v_L + \sqrt{h_R}v_R}{\sqrt{h_L} + \sqrt{h_R}}, \; \tilde{c} = \sqrt{g\frac{h_L + h_R}{2}}$$

To distribute flux difference according to characteristic velocity, for example, numerical flux $\boldsymbol{F_x}$ is as follow. In the case of subcritical flow, numerical flux difference is distributed to up and downstream calculation point. In the case of supercritical flow, numerical flux difference is distributed to only downstream calculation point.

$$(\tilde{\boldsymbol{e}}_x\tilde{\boldsymbol{\lambda}}_x\tilde{\boldsymbol{e}}_x^{-1})\frac{\partial \boldsymbol{U}}{\partial x}_i = \tilde{\boldsymbol{e}}_{x(i-1/2)}\frac{\tilde{\boldsymbol{\lambda}}_{x(i-1/2)} + \left|\tilde{\boldsymbol{\lambda}}_{x(i-1/2)}\right|}{2}\tilde{\boldsymbol{e}}^{-1}_{x(i-1/2)}\frac{\Delta \boldsymbol{U}_{(i-1/2)}}{\Delta x} + \tilde{\boldsymbol{e}}_{x(i+1/2)}\frac{\tilde{\boldsymbol{\lambda}}_{x(i+1/2)} - \left|\tilde{\boldsymbol{\lambda}}_{x(i+1/2)}\right|}{2}\tilde{\boldsymbol{e}}^{-1}_{x(i+1/2)}\frac{\Delta \boldsymbol{U}_{(i+1/2)}}{\Delta x}$$

$$\boldsymbol{F}_x = \left(\boldsymbol{E}_L + \boldsymbol{E}_R - \tilde{\boldsymbol{e}}_x\left|\tilde{\boldsymbol{\lambda}}_x\right|\tilde{\boldsymbol{e}}_x^{-1}\Delta \boldsymbol{U}\right)/2 \tag{5}$$

Characteristic velocity $|\tilde{\lambda}_x|$ is represented by following function $\Psi(\tilde{\lambda}_x)$ to remove non-physical expansion shock wave, because numerical flux of equation (5) do not satisfy entropy condition.

$$\boldsymbol{\Psi}(\tilde{\boldsymbol{\lambda}}_x) = \begin{cases} \left|\tilde{\boldsymbol{\lambda}}_x\right| & \text{if} \quad \left|\tilde{\boldsymbol{\lambda}}_x\right| \geq 0.5\boldsymbol{d}_x \\ \tilde{\boldsymbol{\lambda}}_x^{\,2}\boldsymbol{d}_x^{-1} + 0.25\boldsymbol{d}_x & \text{if} \quad \left|\tilde{\boldsymbol{\lambda}}_x\right| < 0.5\boldsymbol{d}_x \end{cases}$$

$$\boldsymbol{d}_x = \max\left[\boldsymbol{0}, 4(\boldsymbol{\lambda}_{xR} - \boldsymbol{\lambda}_{xL})\right]$$

In the same way, numerical flux on y-axis is discritized. Gravity term is discritized by direction of characteristic wave as well as pressure term.

5 NUMERICAL EXPRESSION OF THE FLOOD DAMAGE AND MODELING OF HOUSE TO BE SWEPT AWAY

Photo 1 shows location of houses and warehouses to be swept away on aerial photograph before flood

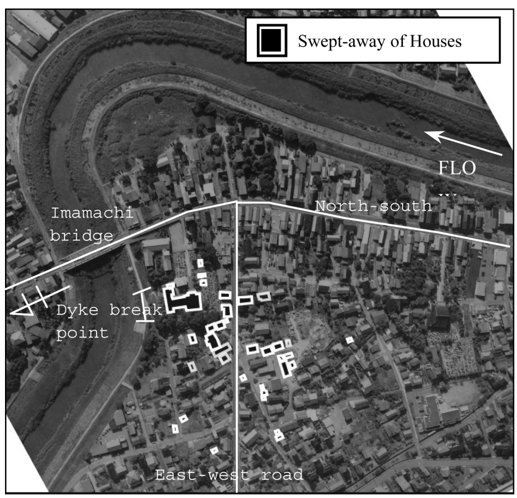

Photo 1. Nakanoshima floodplain in Kariyata River and location of houses to be swept away.

disaster. Photo 2 shows contour lines of height of sediment deposition on aerial photograph after flood disaster. Houses to be washed out gathered along east-west road and around broken dyke. It is understood that local scour by flooding flow expands in the west floodplain from dike break point of Kariyata River and sediment deposition is larger in direction across left dike and along east-west road. Figure 1 shows floodplain elevation after flood disaster, which is taken by laser profiler, sediment deposition showed in Photo 2, and houses location from electronic map. It is understood from these data and aerial photograph that sixteen houses and warehouses including a temple near dyke break point were swept away. Houses and dyke in Figure 1 is introduced as impermeable boundary condition. Elevation within the enclosure of left dyke and north-south road in the figure is higher than that of the area where houses was swept away and great sediment was deposited. Flooding flow by dyke break is thought to be mainly two flows. One is vertical direction flow against the left dyke which gradient of water surface is largest immediately after the dyke is broken. Another is flow along east-west road which resistance against flood flow is smaller.

Figure 2 is organized eyewitness report about dyke break width in July and August 2004. In the numerical analysis, dyke break width is increased at interval of 2 m as given condition from these reports. One of the eyewitness who bank up sandbags on the dyke give testimony that earth on back slope of the dyke was scoured at first, revetment concrete blocks remained baldly, flood ran off toward housing estate at a blast as soon as the revetment blocks was broken and a temple which flood hit directly was broken down in front of his eyes. And the dyke break was seeing to be widening downstream. Swept-away of house is mainly caused by water pressure with rising water level on upstream face of house. In numerical analysis, house is swept away when moment acting on downstream bases of house is over threshold value. The threshold value is decided from information of houses to be swept away in TV news taken after about 8 minutes after left dyke break. In numerical analysis, after the house is swept away, grids of house are changed into grids that flood flows. Hydrodynamic force $\boldsymbol{F}$ and moment $\boldsymbol{M}$ calculated by the following equation.

$$\boldsymbol{F} = \oint\left(\rho g h^2/2\right)\boldsymbol{n}\,ds, \quad \boldsymbol{M} = \oint\left(\rho g h^3/6\right)\boldsymbol{n}\,ds \tag{6}$$

where $\boldsymbol{n}$ is unit vector which inside direction of house boundary is positive and ds is differentiation around house boundary.

Photo 2. Floodplain damaged and contours of sediment deposition height (unit: cm).

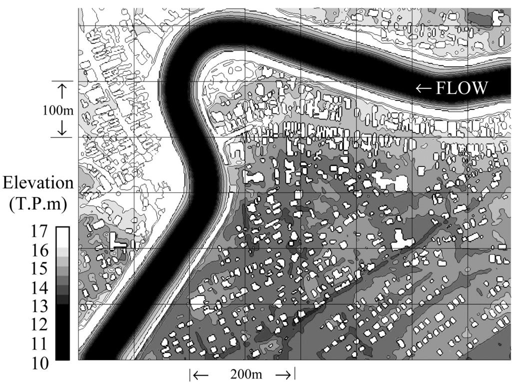

Figure 1. Floodplain topography in Nakanoshima.

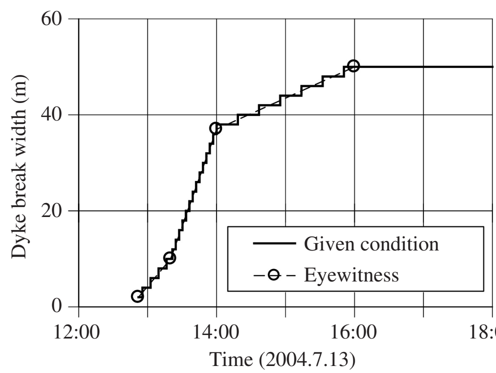

Figure 2. Dyke break width of eyewitness report and given condition in the calculation.

6 CALCULATED CONDITION AND REPRESENTABILITY FOR FLOOD FLOW

It is thought that momentum flux in Kariyata River affected flow in floodplain strongly because of information about flood flow and dyke break of previous section. Therefore, flood flow is represented in the river from 9 to 9.88 km from confluence for Shinano River and in the floodplain of 680 m × 634 m which included houses to be swept away (Figure 6). It is calculated from 12:00 to 18:00 in July 13, 2004 (Figure 3).

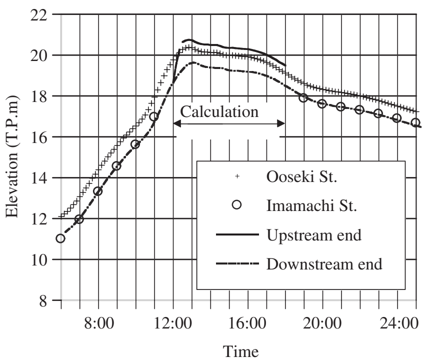

Figure 3. Boundary condition in upstream and downstream end.

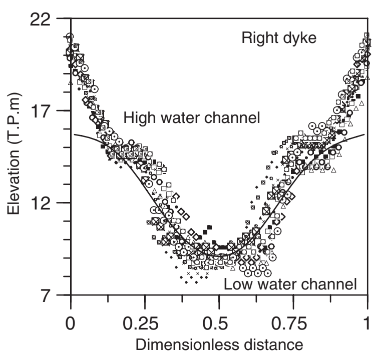

Figure 4. Cross-sectional profile in the Kariyata River.

It is given as calculation condition that $dx = dy = 2$ m, $dt = 0.05$ sec, Manning's roughness coefficient $n = 0.035$ in the river channel and $n = 0.02$ in the floodplain. Upstream and downstream condition of Kariyata River in the calculated area is given by water level data interpolated from Ooseki observation station at about 10.5 km, Imamachi observation station at about 8.8 km and trace data on right and left dyke in Figure 5. Figure 4 shows bed profile data in observation and calculation. Vertical wall and approximate value of observed bed profile data is given in consideration of stability of numerical model. A part of high water channel revetment remained and high water channel did not scoured in the place where dyke was broken in Photo 3. In the calculation, floodplain elevation nearby dyke break point is given in grid to flow newly after dyke is lost.

Figure 5 shows maximum water level among flood in calculation and observation. It is represented in calculation that longitudinal profile of traced water level in observation and difference of water level between left and right dyke by centrifugal force in bending section at 9.6 km.

Figure 6 shows calculated maximum water depth and traced water depth in floodplain measured in the field. Figure 6 shows projection into each axis. Calculated maximum depth is recorded at 3 hours 14 minutes after left dyke break. Water depth is also shown at grids of houses to be swept away. Developed numerical model could represent water depth with good accuracy around the broken dyke, in the direction across the left dyke and along east-west road.

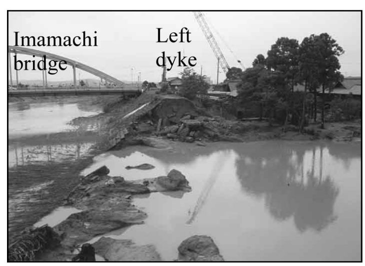

Photo 3. Situation of dyke break.

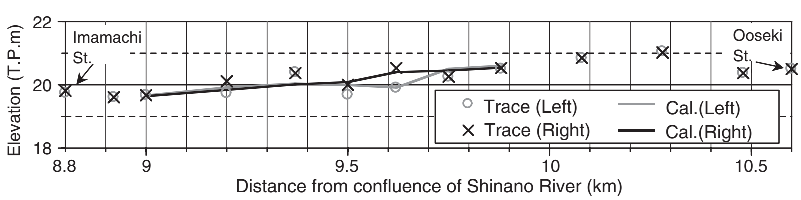

Figure 5. Trace water level on left and right dyke and maximum calculated water level.

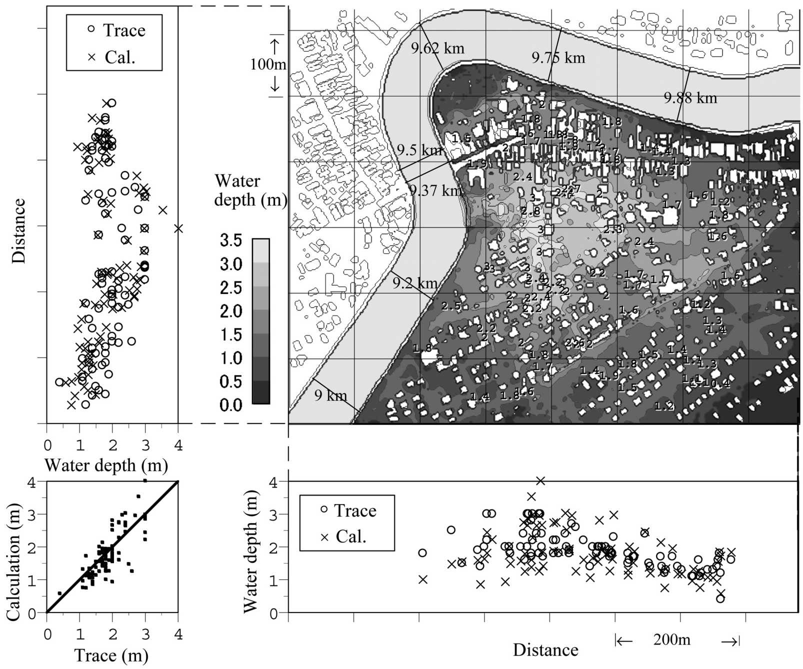

Figure 6. Trace water depth in floodplain and calculated maximum water depth (at 3 hours and 14 minutes after dyke break).

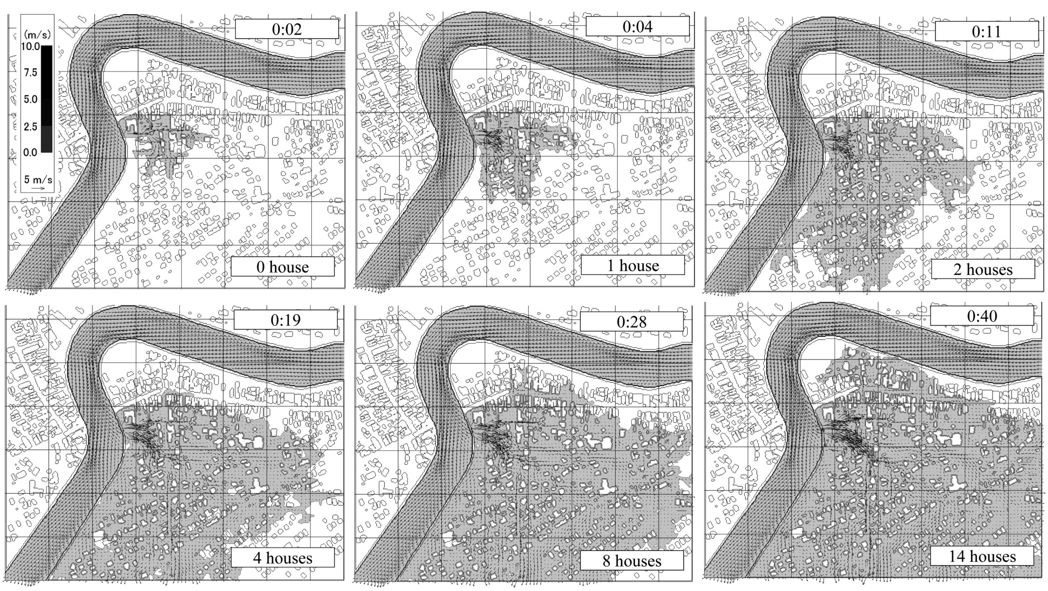

Figure 7. Calculation results of velocity vector, inundated district and total number of houses to be swept away immediately after dyke break (from 2 minutes to 40 minutes after dyke break).

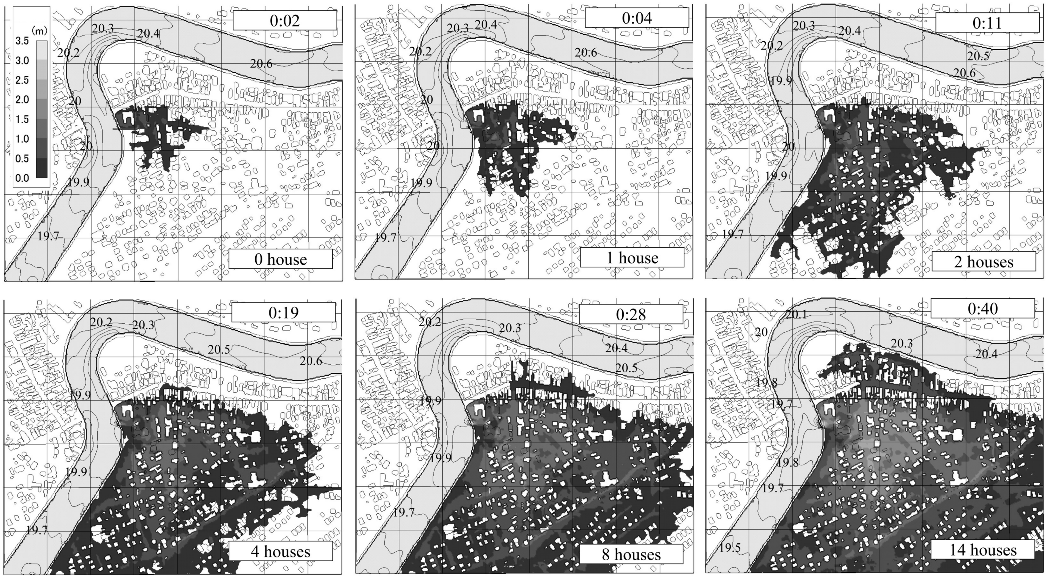

Figure 8. Calculation results of water level in the river channel, water depth in floodplain and total number of houses to be swept away immediately after dyke break (from 2 minutes to 40 minutes after dyke break)

7 SWEPT-AWAY OF HOUSES BY FLOOD FLOW

Figure 7 shows calculation results of velocity vector averaged in water depth and inundated district from 2 to 40 minutes after dyke break. The velocity vector is changed length and color according to magnitude. It is understood that the velocity of flooding flow near dyke break point is more than 7 m/s and the velocity inside bending section of river channel is about 3 m/s. The inundated district is decided by threshold value 0.003 m. The inundated district is the area where water depth is more than 0.003 m.

Figure 8 shows contours of water level in river channel at intervals of 0.1 m and water depth distribution in floodplain from 2 to 40 minutes after dyke break. Grids that houses were not swept away are not calculated because houses were not submerged in field data.

Flood flows along north side of temple at 2 minutes after dyke break. And the direction of the velocity vector near dyke break point is toward southeast at the same time. The temple is swept away and the velocity vector changes toward southwest at 4 minutes after dyke break. Comparing with two water surfaces at 2 and 4 minutes after dyke break, longitudinal gradient of water surface along left dyke is larger in the upstream of dyke break point and smaller in the downstream. The velocity vector toward southwest gets bigger when dyke break width is larger. The above-mentioned tendency about water surface in the river strengthens.

The reason that direction of velocity vector changes southeast into southwest is as follows.

(1) Gradient of water surface nearby dyke break point is largest in direction across the left dyke immediately after dyke break.
(2) Beginning to widen dyke break, gradient of water surface is larger at upstream of dyke break point with degradation of water surface.

Flood flow running off from the river after the dyke break is affected by the river flow. Total 1, 2, 4, 8 and 14 houses were swept away at 4, 11, 19, 28 and 40 minutes respectively after the dyke break.

8 CONCLUSION

We developed new numerical analysis model by FDS method for abrupt flooding flow and swept-away of houses. We made clear the relationship between the flood flow from the Kariyata River and swept-away of houses due to dyke break using the numerical model. Useful flood simulation model for floodplain risk management is proposed.

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