

Modeling of Levee-Break Inundation under Extreme Flood for Risk Analysis

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1. Introduction

Under the climate change conditions, extreme floods occur more frequently and leading to increased risks of flooding. Therefore, there is a need to model flood inundation due to levee break accurately. Information obtained from that kind of model will be useful for developing emergency measures. This study investigates the inundation process in the northeast region of the Tokyo metropolitan with assumption of levee break at right side of Tone River under extreme condition similar in size to the Kathleen typhoon on September 16th 1947, which caused the most catastrophic flood in history to the area. About 340 m length of embankment was broken at Kurihashi, in the middle reach of the Tone River (Fig. 1). The resultant floodwater rapidly expanded of about 60 km downstream to the Tokyo metropolitan within only two days, killed more than 1,000 people and caused great damage in the Kanto area. The purpose of the study is to use the model to simulate and then investigate flood inundation processes under the present topography and land uses conditions with extreme inflow flood discharges caused by climate change for mega-urban areas like Tokyo.

2. Input data and numerical model

Topographic and flood discharge data: In this study, topography data used 100 m resolution DEM data (available in ICHARM), which was originally derived from LiDAR data (MLIT, 2005). It should be mentioned in here that, in order to accurately estimate the discharge through the breach, a levee breaching model that correctly simulates the levee breaching process is needed. The problem is more complicated by the fact that could occur either by overtopping or piping modes, and the outflow depends on development of breach by time. This aspect of the problem is out of range of this study, and it is not discussed in here. We use flood discharge at breached point available in PWRI, which estimated by applying flood runoff model with rainfall data is same as to rainfall during the Kathleen typhoon.

Governing equations and numerical scheme: The inundation model is developed based on the two-dimensional (2D), time dependent shallow water equations, including continuity equation (1) and momentum equations (2) and (3):

$$\frac{\partial H}{\partial t} + \frac{\partial(Hu)}{\partial x} + \frac{\partial(Hv)}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - \varepsilon \frac{\partial^2 u}{\partial x^2} - \varepsilon \frac{\partial^2 u}{\partial y^2} = -g \frac{\partial(H+Z)}{\partial x} - \frac{gn^2 u(u^2 + v^2)^{1/2}}{H^{1/3}} \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - \varepsilon \frac{\partial^2 v}{\partial x^2} - \varepsilon \frac{\partial^2 v}{\partial y^2} = -g \frac{\partial(H+Z)}{\partial y} - \frac{gn^2 v(u^2 + v^2)^{1/2}}{H^{1/3}} \quad (3)$$

where t is time, u and v are x and y components of mean velocities, H is water depth, Z is bed elevation, g is acceleration due to gravity, ε is the eddy viscosity coefficient, and n is the Manning coefficient of roughness.

The numerical scheme essentially follows the method of Kawahara *et al.* (1982, 1986). The method applied the weighted residual of the standard Galerkin finite element method (FEM) to the 2D governing equations (1), (2) and (3) for spatial discretization, and employed the selective lumping two-step explicit FEM for numerical integration in time. In the simulation, we used a selective lumping parameter, e , with a value of 0.85~0.9, to reduce the numerical damping effect and to adjust the numerical stability. We used a time increment, $\Delta t = 0.5$ s, in the calculation because the time stepping scheme employed yielded a stable Courant number. Eddy viscosity coefficient ε , which is expressed by a single variable function of the 4/3rd power of the mesh spacing as $\varepsilon = (0.01 \sim 0.02)\Delta^{4/3}$, where Δ is the mesh spacing that can be expressed in terms of the element side lengths, l_1 , l_2 , and l_3 , as $\Delta = (l_1 l_2 l_3)^{1/3}$. The same model has previously been applied and verified for flood flows in Mekong River Delta (Pham T. Hai *et al.*, 2008).

Computational mesh: Regarding the external boundary, we used ArcGIS tool to determine right-side levees of Tone and Edo rivers and high-elevation roads and embankments, where floodwater could not flow overtopping to outside areas, as land boundaries of study area (white line in Fig. 1). A 2D-FEM mesh of the study area was generated by constrained Delaunay triangulation using Mesh-Generator software. In order to generate refined FEM mesh, grid size of elements was selected

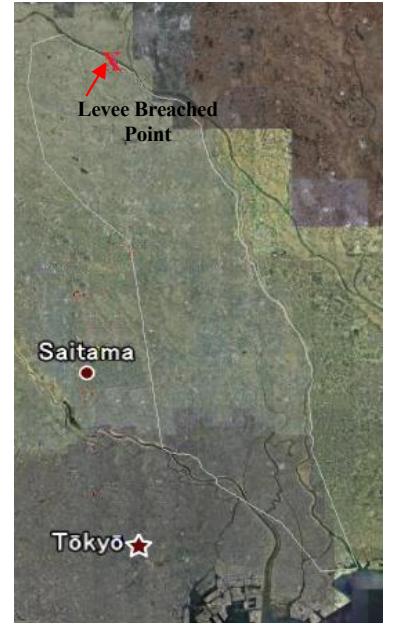


Fig.1. Study area and levee breached point at Tone River

following consideration of the topography, the scale of study area, the time spending and stability of simulation, element side lengths vary from 150 m to 300 m. The final mesh, as shown in Fig. 2 is generated mesh result at levee break point, has total of 25475 nodes and 49998 elements. Based on 100 m x 100 m rater grid topographic data, which created from LiDAR data, elevation of all FEM nodes were interpolated by the bilinear interpolation algorithm.

3. Model application and results discussion

Initial and boundary conditions setting: As for the initial conditions, the right side of levee breach point is initially dry, and then the model was run with a starting velocity and a constant water surface values of zero ($u = 0, v = 0, H = 0$) of all nodes. Lateral slip and no normal flow boundary condition are applied to all nodes belonging to land boundaries. Assuming that the levee was broken at the same point that broke during the Kathleen typhoon in September 1947, we attempted to reproduce inundation process with present topography and land-use. At breach point, all the flow variables u, v , and H of breach FEM nodes were calculated as follows:

$$H = (Q_{br} / CB_{br})^{1/2} ; \quad u = v = -Q_{br} / \sqrt{2}HB_{br} \quad (4)$$

where $B_{br}=340$ m is levee breach length, Q_{br} is discharge at breach point, and C is discharge coefficient in simulation we used $C=1.86$ as reference in Hydraulic formulas handbook.

Simulation results and discussion: As for values of Manning coefficient n , we referred values in Hydraulic formulas handbook depending on land-use; e. g. 0.047 for building and forest lands, 0.025 for grass and farm lands and 0.05 for others. The time step is set to 0.5 s. The simulated results of inundated area and water depth at 3 hrs, 8 hrs and 48hrs after the time of levee breach are showed in Fig. 3 (a), (b) and (c), respectively. After 3 hrs, water depth near breach point is high as 6.0 m and floodwater expanded about 10 km to surrounding area. At 8 hrs after the breach, inundated water with depth of higher than 3.0 m is extended about 31 km to downstream parts, and about 25 km from the breach to western areas. Later on, when the peak of breach discharge slightly decreases, inundated water depth near the breach is declining gradually while floodwater propagates rapidly downstream regions, then water depth is sharply increasing there. Eventually, after 2 days, when the inflow discharge is significantly reduced, water depth around the breach lessens than 2.0 m. At this time, the whole downstream areas are inundated severely with extend about 60 km to the southern. In areas near Edo River levees, the lowest parts in study area, inundated water depth raised more than 3.2 m.

4. Conclusions

For accurate flood inundation simulation, the developed model applied two-dimensional shallow-water equations coupling with finite element method. Model can simulate flood inundation with case of assuming of levee breach in Tone River caused by Kathleen Typhoon in 1947. This model can apply for any area where topographic data is obtainable. In addition, for new updated topographic and land-use data, more validation of the model results with various values of Manning roughness coefficients are expected. Model results like flood arrival times, inundation depths and durations of inundation can be used to generate flood mapping, subsequently uploaded to Web-based interface, making the modeling and presentation process much more comprehensive to the general public. Furthermore, this information can be used by local agencies in development of emergency and evacuation plans and in analyzing risk potential in the event of flooding caused by levee breach.

5. References

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Keywords: levee break, inundation modeling, finite element method, extreme flood, climate change

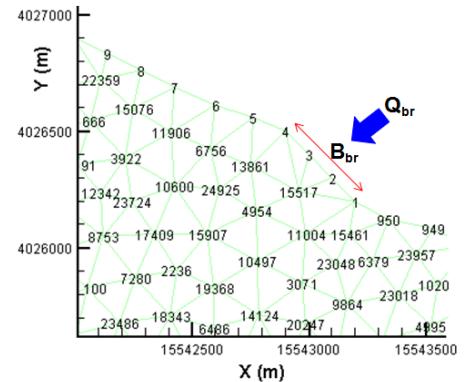


Fig. 2. Generated mesh at levee break point

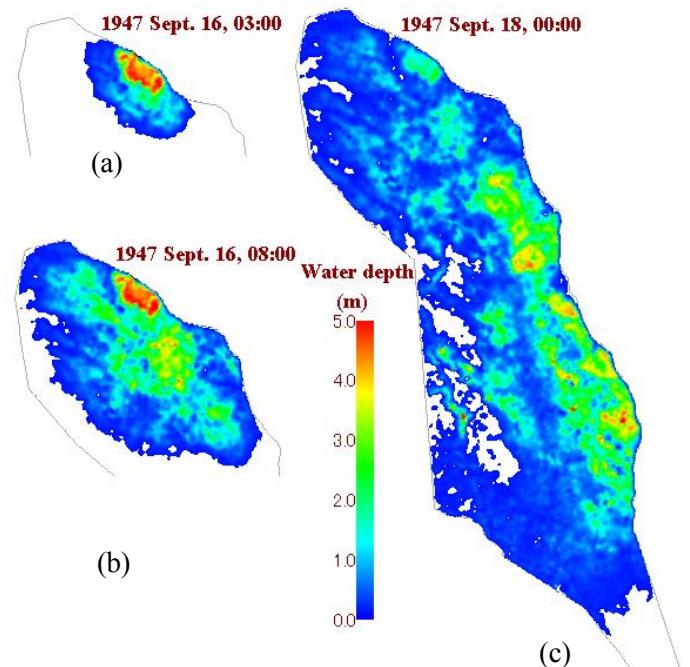


Fig. 3. Prediction inundated area and water depth at 3 hrs (a), 8 hrs (b) and 48 hrs (c)

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