Large-scale flooding analysis in the suburbs of Tokyo Metropolis caused by levee breach of the Tone River using a 2D hydrodynamic model


ABSTRACT

In order to assess the effects of climate change on flood disasters in urban areas, we applied a two dimensional finite element hydrodynamic model (2D-FEM) to simulate flood processes for the case analysis of levee breach caused by Kathleen Typhoon on 16 September 1947 in Kurihashi reach of Tone River, upstream of Tokyo area. The purpose is to use the model to simulate flood inundation processes under the present topography and land-use conditions with impending extreme flood scenarios due to climate change for mega-urban areas like Tokyo. Simulation used 100 m resolution topographic data (in PWRI), which was derived from original LiDAR (Light Detection and Ranging) data, and levee breach hydrographic data in 1947. In this paper, we will describe the application of the model with calibration approach and techniques when applying for such fine spatial resolution in urban environments. The fine unstructured triangular FEM mesh of the model appeared to be the most capable of introducing of constructions like roads/levees in simulations. Model results can be used to generate flood mapping, subsequently uploaded to Google Earth interface, making the modeling and presentation process much comprehensible to the general public.

Key words | dynamic flood simulation, extreme event, finite element method, levee breach, 2D modeling

INTRODUCTION

Climate change will affect many sectors, including water resources, agriculture, ecosystems, human health and so on. There is evidence of prominent increases in the intensity and frequency of many extreme weather events. Under climate change, rainfall increases are predicted over most of the monsoon climate regions. This means, extreme floods could occur more frequently, and leading to increase of flood-prone areas and disastrous events in the affected regions. Therefore, it is vital to accurately and reliably model possible flood inundation due to occurrences like levee breaches etc., that could cause intensified damages and loss of life, especially in densely populated areas.

Information obtained from that kind of modeling approaches will also be useful for developing emergency measures. Such a model is helpful not only for developed countries like Japan but also for the developing countries. This study investigates the inundation process in the northeast region of the Tokyo metropolitan with the assumption of a levee break at the right side of Tone River under extreme condition similar in size to the Kathleen typhoon on 16 September 1947, which caused the most catastrophic flood in history in the area. About 340 m length of embankment was broken at Kurihashi, in the middle reach of the Tone River (Figure 1). The resultant floodwater...
rapidly expanded to about 70 km downstream to the Tokyo metropolitan within only two days, killing more than 1,000 people and causing great damages in the Kanto area. A two dimensional finite element hydrodynamic model was applied for this case to analyze flood inundation processes in the study 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-use conditions with extreme inflow flood discharges caused by climate change for mega-urban areas like Tokyo. Furthermore, differences between model results with recent conditions and past evidences (1947) will be discussed to propose necessary adaptation measures for flood disaster management in area.

MATERIALS AND METHODOLOGY

Topographic and flood discharge data

Topographic data used in this study are based on LiDAR data which are measured and provided by Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan in between 2005 to 2006. In the LiDAR data, elevation data correspond to a mixture of bare earth surface, tree canopies and building tops. This data has accuracy of absolute elevation error of less than 0.15 m. From the original LiDAR data, a 100 m $\times$ 100 m resolution grid DEM data was derived (available in ICHARM) to use as input data to the 2D-FEM model.

It should be mentioned here that, in order to accurately estimate the discharge through the breach, a levee breaching model that correctly simulate the exact breaching process is needed. The problem is more complicated by the fact that it could occur either by overtopping or piping modes, and the outflow depends on the development of breach with time. This aspect of the problem is out of scope of this study, and it is not discussed herein. We used flood discharge at breached point available in PWRI, which was estimated by applying a flood runoff model with rainfall data as same as to that during the Kathleen typhoon. Figure 2 shows the assumed breach hydrograph at specific levee breach point.

Governing equations and numerical scheme

In the study, the flood inundation process, which was caused by the levee breach in Kurihashi, has been modeled using the two-dimensional depth-averaged shallow water Equations (2D-SWE). The governing equations include continuity Equation (1) and momentum Equations (2) and (3):

\[
\frac{\partial H}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0
\]

\[
\frac{\partial (Hu)}{\partial t} + \frac{\partial (Huu)}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial x}
\]

\[
\frac{\partial (Hv)}{\partial t} + \frac{\partial (Huv)}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial y}
\]
\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - e \frac{\partial^2 u}{\partial x^2} - e \frac{\partial^2 u}{\partial y^2} + g \frac{\partial (H + Z)}{\partial x} & + \frac{g n^2 (u^2 + v^2)^{1/2}}{H^{1/3}} = 0 \tag{2} \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - e \frac{\partial^2 v}{\partial x^2} - e \frac{\partial^2 v}{\partial y^2} + g \frac{\partial (H + Z)}{\partial y} & + \frac{g n^2 (u^2 + v^2)^{1/2}}{H^{1/3}} = 0 \tag{3}
\end{align*}
\]

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, \( e \) is the eddy viscosity coefficient, and \( n \) is the Manning's coefficient of roughness.

The numerical scheme essentially follows the method of Kawahara et al. (1982) and Kawahara & Umetsu (1986). The method applies the weighted residual of the standard Galerkin finite element method (FEM) to the 2D governing Equations (1)–(3) for spatial discretization, and employs 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 0.85–0.95, to reduce the numerical damping effect and to adjust the numerical stability. We used a time increment, \( \Delta t = 1.0 \) s, in the calculation because the time stepping scheme employed yielded a stable Courant number. Eddy viscosity coefficient, \( e \), which is expressed by a single variable function of the \( 4/3 \)rd power of the mesh spacing as \( e = (0.01 - 0.02) \Delta^{4/3} \), where \( \Delta \) is the mesh spacing that can be expressed in terms of the element side lengths, \( l_1, l_2, \) and \( l_3 \), as \( \Delta = (l_1 l_2 l_3)^{1/3} \). For simplicity, the eddy viscosity coefficient \( e \) is constantly chosen as \( 10 \) m\(^2\)/s.

**Computational mesh**

Regarding the external boundary (or land boundary), we used Arc-GIS tools to determine right-side levees of Tone and Edo rivers and high-elevation roads and embankments, where floodwater from inside study area could not flow overtopping to the outside areas, as land boundaries of study area (blue line in Figures 1 and 3). 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 following consideration of the topography, the scale of study area, the time spending and stability of simulation, where element side lengths vary from 120 m to 500 m. The final mesh, as shown in Figure 3, is the computational mesh result, which has total of 6,630 nodes and 12,862 elements. Based on the 100 m \( \times \) 100 m raster grid DEM data, which was created from the topographic LiDAR data, elevation of all FEM nodes were interpolated by the bilinear interpolation algorithm.

**MODEL APPLICATION AND DISCUSSION**

**Initial and boundary conditions setting**

The model requires both initial conditions and boundary conditions. As for the initial conditions, the storage area at 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 is breached at the same point that
breached during the Kathleen typhoon in September 1947, we attempted to reproduce inundation process with present topography and land-use. Figure 4 shows generated mesh result at levee break point. At breach point, all the flow variables $u$, $v$, and $H$ of breach FEM nodes were calculated as follows:

$$H = \left( \frac{Q_{br}}{C_{br}B_{br}} \right)^{2/3}; \quad u = v = -\frac{Q_{br}}{\sqrt{2}HB_{br}}$$

where $B_{br} = 360$ 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 referenced in Hydraulic formulas handbook (1999).

Model application and discussion on results

The equations were solved numerically using the two step selective lumped mass scheme. And the scheme is finite element in space and finite deference in time and is explicit. The scheme was solved for $H$, $u$ and $v$ at each half $\Delta t$ of setting time increment. The constant time step $\Delta t$ is set to 1.0 s. As for values of Manning’s coefficient, $n$, we referred to values in Hydraulic formulas handbook depending on land-use; e. g. 0.03 for buildings and forest lands, 0.025 for grass and farm lands and 0.035 for others. Exchange discharges, conversion between inside and outside of land boundary, like inflows (except for breach discharge), outflows, evaporation and infiltration are not introduced in the simulations. In fact, to validate the model we have to reproduce the event with original hydrology and topography conditions for the area. But it is impossible task to gain the past/historical data like topography/land-use, flood-traces etc. in this case. And in this study, the model is used as a tool to investigate flood inundation processes under the present topography and land uses conditions with extreme inflow flood discharges like caused by historical Kathleen Typhoon in year 1947, so it is hard to judge the model in here. The same model has previously been applied and verified for flood inundation processes in Mekong River Delta (Pham et al. 2008). In the study, the details of roads, levees, road-opening works, small canals, etc. were introduced in the model with very high resolution of simulation meshes (124,997 elements and 62,965 nodes), and the model’s results showed that it can robustly and well simulate various typical floods as recent extreme and drought flood flows for a macro-area like Mekong River Delta with a long term of simulations.

The simulated results of inundated area and water depth at 2 hrs, 3 hrs, 6 hrs, 12 hrs, 24 hrs and 48 hrs after the time of levee breach are showed in Figure 5. After 3 hrs, water depth near breach point is high as 6.0 m and floodwater expanded about 10 km to surrounding area. At 12 hrs after the breach, inundated water with depth of higher than 3.0 m is extended about 26 km to downstream parts, and about 23 km from the breach to western areas. Later on, when the peak of breach discharge slightly decreases, inundated water depth near the breach declines gradually while floodwater propagates rapidly to downstream regions, causing water depth there to increase sharply. Downstream inundation expanding reached about more than 46 km after one day. Eventually, after 2 days, when the inflow discharge is significantly reduced, water depth around the breach lessened to less than 2.0 m. At this time, the whole downstream areas are severely inundated with an extent of about 60 km to the southern areas. In areas near Edo River levees, in the lowest parts of the study area, inundated water depth raised to more than 3.2 m. The past flood processes of real inundation in September, 1947 at study area took longer time. It took 2 days to expand to half way from upstream to downstream and full 4 days to reach to downstream end of the area. Reasons for differences between real and simulation result should be the surface subsidence with time in the study area that has made the
ground elevation at downstream area lower than that in the past, and Manning's coefficients used in the present simulations are slightly smaller, making the simulation flow more rapid in comparison with real flood flows. In addition, the mesh sizes used in simulations vary from 120 m to 500 m and were rather large, so that the small roads, building blocks etc. with their actual widths of less than 120 m could not be well introduced into the model. The model can easily generate a higher resolution of simulation meshes (for example, from 10 m to 50 m) to introduce these construction works into the model. However, we also need huge extra field investigations and more detail data treatments. And as a consequence, simulation time will significantly increase. For obstructions due to urban infrastructure, the model needs to use higher values of roughness coefficients (Begnudelli & Sanders 2007; Sanders et al. 2008). Furthermore, the present simulation has not yet considered obstructions due to high elevation constructions like highways, small dikes as well as drainage works like channel and sewers. The obstruction works could delay propagation process of flood to downstream, and increase inundation depth at upstream, while harmonious operation of drainage pump systems and channels coupling with sewer networks could quickly decrease inundation depth and area, significantly mitigating the risks and losses in the region.

Figure 5 | Predicted inundation area and water depth at 2, 3, 6, 12 and 48 hrs after the breach.
CONCLUDING REMARKS

For accurate flood inundation simulation, the developed model applied two-dimensional shallow-water equations coupled with finite element method. With the purpose of the study is to use the model to simulate and then investigate flood inundation processes under extreme inflow flood discharges caused by climate change for mega-urban areas like Tokyo, the model can adequately simulate flood inundation in the case of an assumed levee breach in Tone River, similar to that caused by Kathleen Typhoon in 1947. This model can also be applied to any area where topographic data is obtainable. In addition, for recently updated topographic and land-use data, further verification of the model results with various values of Manning’s roughness coefficients is necessary. 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, presentation, and probably required evacuation processes much more comprehensible to the general public. Figure 6 is an example of uploading predicted inundation results into the Google-Earth. When gain access into this data, the basin managers and general public can easily know the exact inundated areas, maximum water depths, flood flow velocity with values and directions, and expected duration of inundation. Furthermore, this information can be very helpful to the local agencies in the development of emergency and evacuation plans and in analyzing risk potential in the event of flooding caused by levee breach.

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