MODELING OF URBAN FLOODING INCLUDING UNDERGROUND SPACE

SRIKANTHA HERATH
Environment and Sustainable Development Program, United Nations University
5-53-70, Jingumae, Shibuya-ku, Tokyo 150-8925, Japan

DUSHMANTHA DUTTA
Institute of Industrial Science, The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

Urban expansion takes place not only in the two dimensional horizontal plane, but both upwards and downwards in the vertical domain. With the increased number of underground facilities, safety issues of underground spaces against natural disasters have become an important aspect of urban safety. This paper describes floods in underground facilities in Japan in the last three decades and presents a 3D modeling system designed for simulating urban floods including underground facilities. The flood modeling system consist of a distributed hydrological model coupled to a one dimensional river network system using diffusive model and a coupled 2D diffusive model for the surface flooding. A case study application of the model in the Fukuoka City of Japan is demonstrated. The inflow into the subsurface are modeled according to the subsurface openings in each simulated grid. Horizontal resolution of 20 m grid data sets have been used in the modeling and DEM and DSM data have been used to delineate the buildings from the spatial information. The simulation has shown that the overflow over embankment, overland flood wave propagation and flood heights could recreate the observed conditions. The water quantities entering to the underground space too, match well with the reported figures.

INTRODUCTION

Mega cities are expanding not only in the 2dimensional surface, but also vertically both upward and downward. Most of the time such expansion is carried out without adequate knowledge on the associated risks. Especially the underground expansions are vulnerable to flooding, as witnessed in the fatal drowning cases in Japan, or fires, explosions, etc. Often the risks associated with these events are unknown, as they have not been used sufficiently long to be exposed to such hazards. Nevertheless, concentration of people and wealth at such underground spaces are expanding and merits careful examination. One way of overcoming the difficulty of lack of past experience is to model the risks by simulating the physical phenomena and their impact on people and property located in the cities at any given time.

Modeling urban floods incorporating densely distributed urban infrastructure poses several difficulties. The flow of water over the surface is determined by small differences
in elevation, which makes it necessary to utilize high-resolution elevation data in the modeling. In addition, various urban infrastructures determine the open and closed flow paths. This requires gathering and employing very high-resolution spatial data that also incorporate infrastructure information. Most of the cities in Japan have underground facilities including subway public transport facilities, business and commercial facilities, which are under threat of flood water. In the past, there have been several large urban flood events that caused much economic damage to underground facilities.

The inflow of overland flow to the underground spaces is determined by the height of uncovered entrance to the underground spaces. This requires collection of information pertaining to individual buildings that describes floor heights as well as the elevation of various entrances. Finally, the risk of underground flooding is determined by the sizes of the underground space as well as how such individual spaces are connected to each other. Because of the interconnections between subway rail systems, floodwater can be routed for considerable distances away from the source of flooding (Compton et al., [1]). Unlike, surface maps, there are no continuous subsurface maps. Although underground structures are often connected through passageways, each individual space is referred in relation to the building over the ground. It is necessary to construct underground space and its connectivity from such information. This paper describes the underground flooding background in Japan, a mathematical model to predict underground inundation and an application.

UNDERGROUND FLOODING IN JAPAN

Most of the Japanese cities are located in floodplain. There have been several events of flooding to underground facilities recently due to rapid expansion of underground facilities in many cities. Most of these floods severely affected the underground railway transport systems. Two such major events in 1999 caused two fatal accidents. One was in Fukuoka, and another in Shinjuku ward in Tokyo. In both these cases, victims were drowned in underground space.

Flooding in underground facilities in Tokyo are more frequent compared to other cities, which can be attributed to the high density of underground facilities located in Tokyo. The records of underground flooding in Tokyo during 1999 to 2001 identify 17 underground flooding events (TMG [12] & [13]). Most of these events occurred in summer during the period of July to September that includes the rainy season and typhoon period. There were 6 events in 1999, 7 in 2000 and 4 in 2001. Total number of flooded buildings was 179 in 1999, 102 in 2000 and 56 in 2001. Total extent of flooded floor area was 116,554m$^2$ in 1999, 14,251m$^2$ in 2000 and 5,502m$^2$ in 2001. The inundated area in 1999 was about ten tiles larger than that of the other two years and has caused inundation of higher number of buildings. There was a large variation of maximum hourly rainfall during these events from 44mm/hr to 131 mm/hr, with an average of about 60mm/hr. A total of 17 events in Tokyo within these 3 years clearly show the seriousness of the underground flooding in major urban cities.
MODEL DESCRIPTION

The physically based distributed hydrologic model, used in this study, was developed in the University of Tokyo, Japan (Herath et al., [5], Jha et al., [7], Dutta et al., [2]). It considers five major components of hydrological cycle, which are; Interception and evapotranspiration, river flow, overland flow, unsaturated zone flow and Saturated zone flow. For all other components, water movement is simulated using the physically based governing equations. The governing equations are solved by finite difference schemes. For River flow, diffusive approximation of the 1-D St.-Venant’s equation is considered. An implicit finite difference scheme is used to solve the governing equations of flow for river network. Similarly, for Overland flow diffusive approximation of the 2-D St-Venant’s momentum equations is considered and the governing equations are solved using an implicit finite difference scheme. For Unsaturated zone flow, 3-D Richard’s equation of unsaturated zone is solved implicitly. 2-D Bossinesq’s equation of Saturated zone flow is solved implicitly. A uniform grid network of square grids is considered for solving the governing equations with finite different schemes.

Within each component, governing equations are solved individually and they are coupled in each time-step of solution for exchange of parameters. The coupling time can be varied depending on the simulation requirement and resolution of input temporal data sets. For the present application of the model, coupling time step is considered as one hour for all the components but overland and river flow. For accurate representation of the dynamic exchange of flow between surface and river flow components, coupling time between these two components are considered as 300 sec. A flood compartment concept is used for coupling of overland and river flow components in which existing embankment heights along the rivers can be incorporated and exchange of flow between surface and river is calculated using a storage routing relation with the assumption of broad-crested weir flow with submergence correction. Flow can be either away from the river or into the river, depending on the relative water depths in adjacent river and surface grids. With this process, flood inundation can be simulated for both inland and river overflow flooding.

![Figure 1. Schematic diagram of concept of 3D urban flood modeling](image)
For the present study, only surface and river components of the model are considered and other components are ignored. The model was modified by incorporating new condition of water flow into underground facilities from surface flow during 2D surface flow simulation process as shown in Figure 1. The following conceptual equation is adopted for calculating flow into underground facilities through the openings. This equation is based on the experiments carried out at the Public Works Research Institute, Japan (Suetsugi, [10]).

\[ Q = 2.3Bh^{1.8} \]  

(1)

Where \( Q \): inflow(\(m^3/s\)), \( B \): opening width(\(m\)), \( h \): water depth on ground(\(m\)).

**MODEL APPLICATION**

**Study Area**

A dense urban area surrounding Hakata railway station of Fukuoka city, Fukuoka Prefecture of Japan, was selected as the study area. With having many underground facilities including the Hakata subway station, this area is one of the most vulnerable areas for floods due to close proximity to Mikasa river. During the past 5 years, two major flooding events occurred in this area (Komaki, [8]; Hashimoto, [3] & [4]; Nishimura, [9]; Tachi et al., [11]; Yamai [15]). The first event occurred in June 29, 1999. The rainfall started in the mid-night of June 28 and continued till June 29. The total amount of rainfall in this event was about 164mm, with the highest intensity of 77 mm/hr that was recorded between 8-9 A.M (Figure 2). Flood inundation occurred around the Hakata station, the major JR and subway station of the Fukuoka City. Mikasa river flows very close to this station from South to North and discharges to Hakata bay, which is located within 5km distance from Hakata station. In this event, initially local inundation of few centimeter occurred due to accumulation of heavy rainfall of 77mm/hr intensity between 8-9A.M., which exceeded the full capacity of the drainage system. Inundation height and volume increased after overflow from Mikasa River started at about 9:00A.M. Flood water entered to Hakata Station about 10:10-10:30 and water went down to subway and other underground facilities near Hakata stations. Flooding caused interruption of the subway train at 12:05 between Nakasukawabata and FukuokaKukou stations. The service was resumed about three and half hours later at 15:46. The volume of floodwater entered into subway was estimated as 2,000m³. According to the railway official of Hakata station, the inundation depth was about 50cm at Chikushi gateway of the station, and the depth of water intruded into the station building was about 10-15cm. There were power failure at the hotels around Chikushi gateway of Hakata station and goods were submerged in the underground mall adjacent to the station. One person was killed by high velocity of floodwater entering into an underground restaurant located at about 400m distance from the JR Hakata station (Toda and Inoue, [14]).
In July 2003, another major urban flood occurred in the same area in Fukuoka. This time rainfall pattern was quite different from the previous event. Although there was heavy rainfall in the upstream of the basin in the mountainous areas, rainfall intensity in Fukuoka city was not high. There were heavy rainfall in Fukuoka prefecture during July 18-19, 2003, especially the Iizuka and Dazaifu stations recorded very high rainfall intensity. At Iizuka station, highest rainfall intensity was 83mm/hr between 03:45-4:45 A.M. and at Dazaifu station, it was 104mm/hr between 03:50- 04:50 A.M. on July 19. Both these stations were located far upstream of Fukuoka city. Rainfall intensities at Fukuoka station during same period were far lesser than those stations with the highest intensity of only 20mm/hr (Figure 4). The flooding in Fukuoka city was caused by overflow of Mikasa River, which was contributed by high inflow from upstream due to heavy upstream rainfall. Flooding in Hakata station started at about 5:30 of July 19, after about 45min of peak rainfall at the two upstream stations. This time, flood inundation extents and heights were much larger than previous event of 1999. Total amount of water entered into the Subway system was estimated at about 10,000 m$^3$, which was 5 times higher than the past event. Observed floodwater height in underground railway line was 1m, which was double of the previous event. The subway train service was suspended between Nakasukawabata and Fukuokakuko Stations from 6:20A.M. It took much more time to resume the service. Operation of subway service was fully resumed after 10:30A.M. of July 20.

These two events show that water can easily enter into the underground facilities once overland flood occurs. The drainage system in Fukuoka city is designed for the rainfall of 5-year return period i.e., an hourly rainfall about 52mm (Inoue et al., [6]; Toda and Inoue, [14]) and same is the situation for most of the other cities. In Fukuoka city, water entered to the subway system within a very short time after overflow of the Mikasa river in the past two flood events as there was no protective measure in place to stop water from entering into the underground facilities. Water entered to the subway system caused much economic damage and inconvenience causing disruption of service.
Simulated Event

The flood event of June 29, 1999 was selected for preliminary application of the 3D model for inundation modeling. Main spatial input datasets for the model; elevation and landuse data; were obtained from airborne laser scanner. In this study, digital surface elevation model (DSM) is used instead of DEM, which is more accurate in flood simulation in dense urban area as it takes into account of the locally elevated ground objects like buildings, highways, etc.

The grid simulation of the spatial dataset was 20m. A total of 25 entrances for underground facilities including subway exist in the study area, through which floodwater can enter to underground facilities. The locations and dimensions of all these openings were defined for calculating the flow into underground facilities. The river cross-section of Mikasa river for every node of simulation was estimated based on the existing cross-section data as 100m interval. Rainfall data from AMEDAS was taken for simulation with hourly interval. The Hourly water level data from the gauging station near the upstream end was considered as upstream boundary condition and for downstream boundary the observed water level at the estuary of Mikasa river was considered. The duration of simulation was 24 hours starting from 01 hour of June 29, 1999 (refer to Figure 2).

Results of simulation

The results of simulation were compared with the observed floods in three categories. These were the comparison of spatial distribution of inundation pattern with the observed inundation pattern, comparison of the maximum inundation at the East and West sides of the Hakata station, and finally the total amount of water entry to the Hakata station. The figure 6 shows snap shots of simulated inundation maps. Not only the inundation patterns but also the overflow locations of the embankment match with the observations. The simulated maximum inundation levels are in close agreement with the observed maximum levels differing only by an order or few cms. Figure 7 shows the simulated inundation depths against the observed maximums. Finally, the total amount of water that has entered the subway has been simulated as 2017 m$^3$ whereas the amount pumped out by the station pumps were reported as 1320 m$^3$. Compared with the uncertainties
associated with water dispersion, we may consider this discrepancy as acceptable, as the reported figures are based on pumping from the station.

![Figure 6. Simulated flood inundations at different times of simulation period](image)

![Figure 7. The observed maximums at the East and West sides of Sakata Station](image)

**CONCLUSION**

The present simulation has integrated river overflow, surface inundation and water entry to subsurface spaces. The simulation has provided the total amount of water that enters the underground space as a function of time that helps to estimate the degree of inundation. As seen from the amount of water entered to Hakata station, the real threat to life in underground space depends on the open space available for water to spread. As the
station has a much larger connected underground floor space consisting of facilities and passenger areas spanning 3 floors and a large commercial area, the underground inundation level was not a threat. However, for underground spaces with smaller floor areas the flooding can be extremely dangerous. Therefore, it is important either to make underground spaces interconnected so that there is enough space for water to spread out, or to make the floodgates that would prevent water entry to the underground space.

When urban disasters are considered, risk reduction measures should not focus on a particular hazard, but should take a multi-hazard risk reduction strategy. From this viewpoint, it is of importance to recognize while underground flood risk reduction would require inter-connected underground spaces, fire risk reduction measures would demand facilities to compartmentalize and contain a fire hazard. Measures that are compatible with both requirements, such as doors that have large open or a flexible bottom should be found in such cases. In addition to flood risk, underground spaces also poses structural dangers, as some of the facilities, such as ventilation ducts are not designed to hold a large amount of water load, such as that would result from an underground flood.

The data available for modeling urban risks are becoming increasingly of better quality. However, information related to underground space is still very sparse and are difficult to obtain. Efforts should be made to compile scattered information related to underground spaces and make them available for risk assessment purposes. Further, it is necessary to find methodologies to estimate the users and user distribution in underground spaces in order to assess risks and design effective infrastructure.

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REFERENCES


