UNDERSTANDING FLOOD BEHAVIOR IN UNDERGROUND FACILITIES FOR URBAN FLOOD RISK MANAGEMENT

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ABSTRACT

Due to high growth of population and rapid urbanization, there is a growing shortage of space especially in urban areas in many countries including Japan. This has led to an increased exploitation of underground space by moving certain facilities and functions such public transport, commercial facilities, etc. to underground. With the increased number of underground facilities, safety issues of underground spaces against natural disasters have become an important aspect of urban safety. Underground facilities located in flood prone areas are very much vulnerable to flood disasters. Most of the cities in Japan have a large number of underground facilities including public transport (subway) and commercial facilities like shopping malls, office space, etc. As most of the cities are located in floodplain, these facilities are always under threat of floods. Urban floods have been causing havoc to underground facilities in Japan time to time.

This paper focuses on understanding the flood characteristics in underground facilities in Japan and modeling such characteristics for risk management. The first half of the paper summarizes floods in underground facilities in Japan in the last three decades and analyzes the characteristics of some of the recent events. The second half presents a generic object oriented algorithm designed for simulating underground flooding. The model is developed using JAVA programming language with the objective of integrating it to a 2D surface inundation model for flood risk analysis in urban cities. Several test runs of the model are carried out in a conceptualized underground subway to analyze its performance.

2. INTRODUCTION

Although great improvements in saving lives during floods have been made over the past century, financial and economic losses from flooding are mounting (White et al., 2001). Extensive efforts in structural mitigation have helped to protect increasingly urbanized areas. However, extreme events can overwhelm structural mitigation measures such as levees and dams; conversely, unanticipated failures of the structural measures can occur during less severe events. When this happens, the damages can be extreme. One of the significant components of impacts from floods is the possibility of damage to underground facilities including transportation infrastructure. Subway lines are particularly vulnerable to flooding, as they are often located below grade and thus can be completely inundated when surface water levels are only tens of centimeters. Because of the interconnections between subway grade systems, floodwater can be routed for considerable distances away from the source of flooding (Compton et al., 2002). Managing the risks to subways can pose dilemmas for decision makers. Implementing or improving structural measures to protect against very rare events can become very costly.

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. Two fatal accidents occurred in 1999.

The first half of the paper provides a summary of past floods in underground facilities in Japan in the last three decades and analyzes the characteristics of some of the recent events. The second half presents a generic object oriented algorithm for simulating underground flooding, which is written in JAVA and designed for integrating with a 2D surface inundation model for urban flood risk analysis. Several test runs of the model are carried out in a conceptualized underground subway to evaluate its performance.

2. BACKGROUND

2.1 Underground flooding in Japan

Most of the Japanese cities are located in floodplain. There have been several events of flooding to underground facilities due to dense underground facilities in many cities. Most of these floods severely affected the underground railway transport systems. Table 1 shows a list of the flood inundation entered into large-scale underground facilities in the past three decades. 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 due to the highest number of underground facilities located in Tokyo. Table 1 shows the record of underground flooding in Tokyo during 1999 to 2001 (TMG 2002 & 2003). 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 folds larger than that of the other two years and that 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 this Mega City.

Table 1: Inundation into underground facility in Japan (Suetsugi, 2000).

Structure	Date	Location	Remarks
Subway	Aug.,1973	Nagoya,	water depth 40cm Rain 80mm/hr
	July, 1981	Uchi-Saiwai Station, Mita Line, Tokyo	
	July, 1985	Nishi-Magome St, Asakusa Line, Tokyo	
	Aug., 1986	Sendai	
	July, 1987	Keihan Line,	River water
	Aug., 1989	Gotanda Station, Asakusa Line, Tokyo	Rain 70mm/hr
	Aug., 1993	Akasaka-Mitsuke Station, Marunouchi-Line, Tokyo	
	June, 1999	Hakata Station, Fukuoka	Rain 77mm/hr
	Aug., 1999	Shibuya Station, Hanzomon Line, Tokyo	
	Aug., 1999	Tameike-Sanno Station, Ginza Line, Tokyo	
	July, 2003	Hakata Station, Fukuoka	
Under-ground Space	1970	Yaesu	
	1982	Subnade Shinjuku	
	Sept.,1983	Central Perk, Nagoya	
	June, 1999	Hakata Station, Tenjin	

2.2 Characteristics of two recent underground flooding in Japan

Recently, there were two major underground flooding in Fukuoka City, Fukuoka Prefecture of Japan within a span of 4 years (Komaki, 2000; Hashimoto, 2001 & 2003; Nishimura, 2000; Tachi et al., 2001; Yanai 2000). 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 (Fig. 1). 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. Figure 2 shows the location of Hakata station and Mikasa river together with demarcated boundary of the maximum recorded flood extent. 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.

Table 2: Underground facility flood in Tokyo

Date	Location (name of ward)	No. of building flooded	Flooded floor area (m2)	Flood Depth (m)	Max hrly rainfall (mm)	Max total rainfall (mm)
1999.7.13	Koto	1	1,800	0.6	44	206
1999.7.21	Shinjuku, Setagaya, Nakano Suginami	42	3,214	0.1-2.45	131	151
1999.8.13-1999.8.14	Nakano, Suginami Koganei	6	674	0.05-1.2	60	422
1999.8.24	Nakano, Toshima	2	72	0.15-0.3	71	75
1999.8.29	Minato, Koto, Shinagawa, Meguro, Setagaya, Shibuya, Nakano, Toshima	126	110,691	0.05-1.5	115	128
1999.9.4	Suginami	2	103	0.4-0.7	58	89
2000.5.15	Minato	2	60	0.05	60	94
2000.7.3	Minato, Shibuya	6	415	0.05-1.02	62	64
2000.7.4	Chiyoda, Minato, Shinjuku, Koto, Kita, Shibuya	57	10,733	0.05-1.6	87	92
2000.7.7-2000.7.8	Suginami, Shibuya, Setagaya	4	430	0.01-0.2	74	264
2000.8.5	Shinjuku, Nakano, Shibuya	3	356	0.1-2	66	72
2000.8.7	Chiyoda, Nerima	6	415	0.05-0.4	59	69
2000.9.11-2000.9.12	Kita, Nakano, Hoya, Kunitachi, Kokubunji, Koganei, Itabashi	24	1,842	0.1-1.2	69	232
2001.7.18-2001.7.19	Shinjuku, Nakano, Nerima,Itabashi	38	2,894	0.1-0.8	109	115
2001.7.25-2001.7.26	Shinjuku, Shibuya, Machida	5	628	0.2-1.7	71	126
2001.9.10-2001.9.12	Chiyoda, Kita, Tama	8	1,805	0.02-0.3	71	699

Inundation height and volume increased after that due to 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 2,000m^3. 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 entered into an underground restaurant located at about 400m distance from the JR Hakata station (Toda and Inoue, 2002).

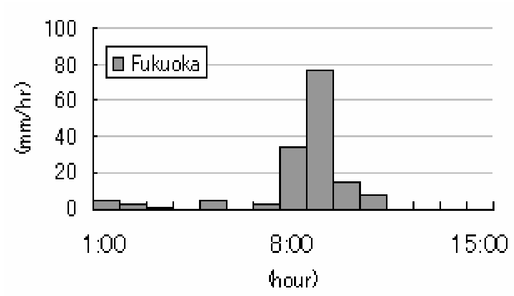


Figure 1: Hourly rainfall pattern at Fukuoka station on June 29, 1999

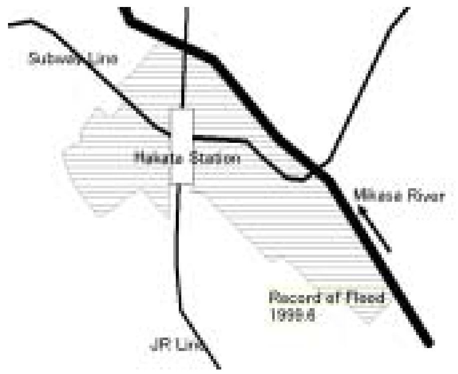


Figure 2: Outline of the Hakata Station, railway lines,
Mikasa River and extent of 1999 floods

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 were 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 (Fig. 3). 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. Oserved 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.

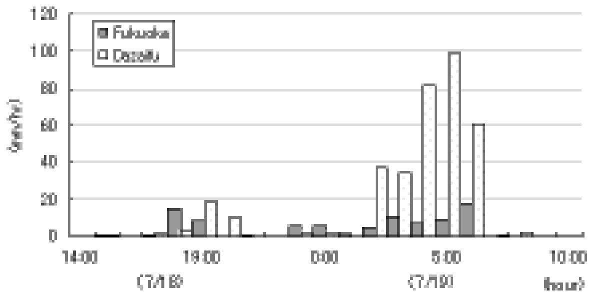


Figure 3: Hourly rainfall pattern at Fukuoka and Dazaifu stations during July 18-19, 2003

Two major underground flood events in the same city within a span of 4 years show the magnitude of problem faced by Japanese cities. These two events show that cities are not designed for very high intensity of rainfall and 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., 2000; Toda and Inoue, 2002) 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 to the system causing disruption of service.

3. MODELING OF FLOODS IN UNDERGROUND FACILITIES

3.1 Modeling Concept

Although there have been frequent floods in underground facilities in Japan, there exists no proper flood control measures and guidelines for most of the underground facilities. It is also important to have properly designed warning and evacuation strategy for real-time flood risk management in the event of any urban flooding. It is very important to analyze the flood characteristics in underground facilities for designing adequate flood control measures and developing guidelines and evacuation strategy to cope with frequent flooding. Due to the complex nature of underground system with many different openings and connections for water movement, very limited attempts have been made so far to model the flow behavior in underground facilities.

This study attempts at developing a generic flow simulation model in underground facilities using an object oriented approach. As it is not possible to conceptualize various underground facilities to a single set of parameters, in the modeling process it is required to have options of adding and dropping any component depending on the type of underground facilities. Object oriented programming concept was adopted for this purpose due to its advantage of expanding model components and introducing various equations easily by adding a class to the model. Also, any new experiment to analyze the performance of additional component can be easily carried out as any class of equation is independent of other classes.

3.2 Defining the components

In this study, object oriented method is adopted for modeling flood characteristics in underground facility and Unified Modeling Language (UML) is used to show the modeling concept in class diagrams, which is the industry-standard language for specifying, visualizing, constructing, and documenting the artifacts of software systems. Figure 4 shows the class diagram with the components of underground facilities considered and how their connections are conceptualized in the model. In general, an underground facility is made of crossing, corridor, pit and opening. Crossing is a conceptual object, which is applied to each end of a corridor. Pit is a vertical or near-vertical space where water can fall and an opening is the top end of a pit where water can flow.

3.3 Classification for simulation

Figure 5 is a class diagram showing how the topology is composed from the objects. One dimensional topology is usually composed of nodes and links. In this case, crossing and opening are nodes, while corridor and pit are links. Equations class defines the relationships between each node and links. As this equations class is independent from other classes, various equations can be easily introduced into this model.

3.4 Governing equations for flow calculation

Various equations classes are designed based on existing conceptual or governing equations of flow and storage behavior in different components of any underground facility. Equation 1 is adopted for defining water depth and flow at openings. This equation is based on the experiments carried out at the Public Works Research Institute, Japan (Suetsugi, 2000). Manning's equation is used to calculate head loss in corridor (Eq. 2).

$$Q = 2.3Bh^{1.8} \tag{1}$$

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

$$v = \frac{1}{n} R^{2/3} i^{1/2} \tag{2}$$

Where v: flow(m/s), n: roughness coefficient, R: radius depth(m), i: slope.

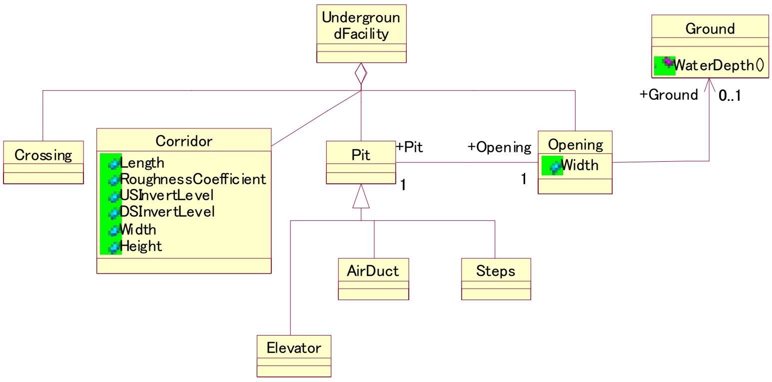


Figure 4: Class diagram of underground facility components

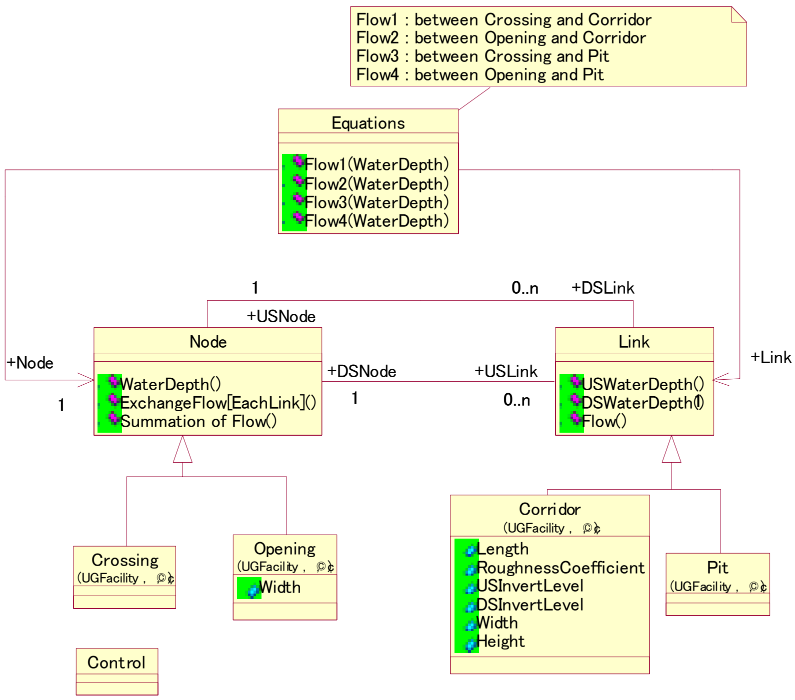


Figure 5: Class diagram of simulation

4. TEST SIMULATION

4.1 Underground facilities as an example

For preliminary testing of the model, a conceptualized underground facility from was adopted (Suetsugi, 2000). It contains the major components of any existing subway station in a city in Japan. However, the dimensions of the facility structure as shown Figure 6 are not realistic. Figure 7 shows the model structure of this underground facility.

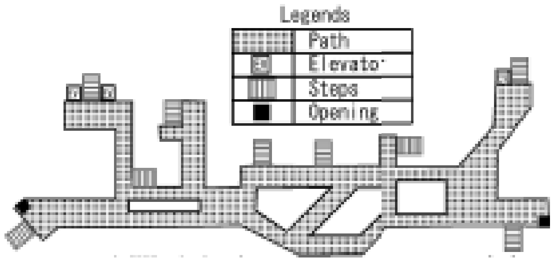


Figure 6: Underground facility structure

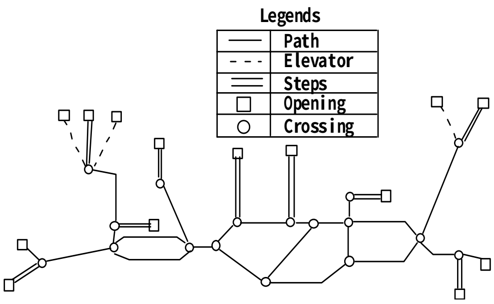


Figure 7: Model of underground facility

For preserving mass balance (with a very rough assumption of static condition for this testing), it is assumed that water volume is constant at any node except the end nodes. Equation 3 represents this condition. As such, flow into node should be positive and flow from node should be negative. For this test simulation, flow from elevator is neglected, and no backwater effect through steps and elevators is considered. Four test runs are carried out with different conditions of surface inundation depths and roughness coefficients as shown in Table 3. Widths of all openings are assumed as 3m.

$$\sum_{i}^{k} q_i = 0 \tag{3}$$

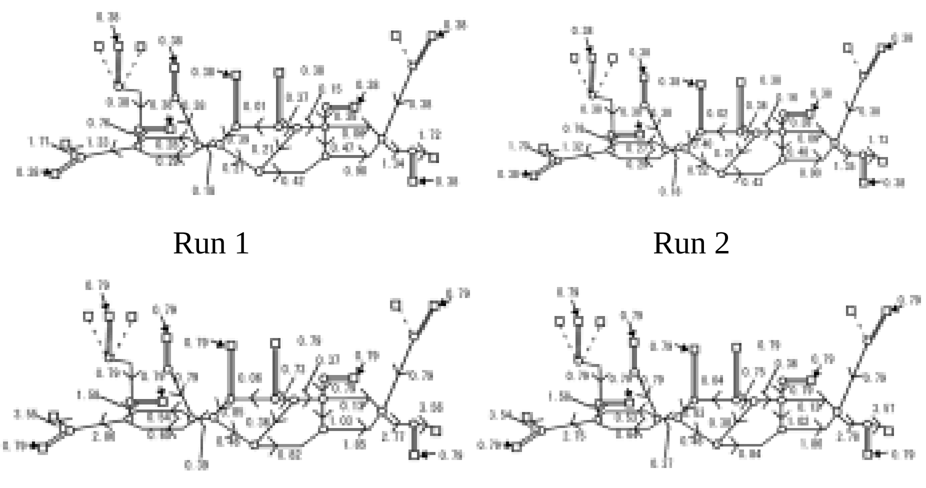
Where k: number of connected links at the node, q_i: inflow to node from i^{th} link.

Table 3: Run conditions

No.	Water depth of surface inundation (m)	Roughness coefficient
Run 1	0.2	0.012
Run 2	0.2	0.03
Run 3	0.3	0.012
Run 4	0.3	0.03

4.3 Results of test simulation

The results of four test runs are shown in Figure 8 where arrows indicate the directions of flow and various numbers represent flow magnitudes in m^3/s. The simulated results show that flow is largely governed by the overland inundation depths and is least influenced by roughness coefficients. There is no mechanism to verify the performance of the system at the moment. However the four test runs show that the designed model can simulate the flow characteristics in different components of underground facilities for different conditions of overland flooding.



Run 1 Run 2

Run 3 Run 4

Figure 8: Calculation Results

5. CONCLUSION

This paper presents a review of flooding in underground facilities in Japan and proposes a model for simulating its behavior. The review shows the seriousness of underground flood problem in various cities in Japan, especially in Tokyo. In 2000, a committee established by the Land, Infrastructure and Transport Ministry of Japan pointed out the importance of various measures for controlling inundation of underground facilities towards mitigating urban flood disasters.

The proposed generic object orientated model for underground facility was tested with sample data for a conceptualized subway station. The test results show that model can simulate the flow behavior in various components of a subway station under different conditions of overland floods. The modeling work is yet to be completed and proper verification of the model is required before evaluating its performance.

Characteristics of surface inundation govern the underground flooding behavior. Volume of water entered to any underground facilities mainly depends on surface flood extent, depth and duration and number of openings. As such, modeling of underground flooding would be useful for urban risk analysis if it is integrated with overland inundation simulation model. The model presented in this study is designed to integrate with a distributed surface inundation model. This 2D grid-based surface model has been developed for urban flood simulation (Dutta et al., 2000). In dense urban areas with many large underground facilities, surface flood inundation is very much influenced by the drainage network and the underground facilities. Therefore such integration is essential for modeling the urban flood behavior adequately.

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