Journal of Hydroscience and Hydraulic Engineering
Vol. 22, No.2 November, 2004, 47-58

INUNDATION ANALYSIS OF COMPLICATED UNDERGROUND SPACE

By

Keiichi Toda

Disaster Prevention Research Institute, Kyoto University, Gokasho Uji, Kyoto, Japan

Kensaku Kuriyama

Toda Construction Co. Ltd., Chuou-ku, Tokyo, Japan

Ryo Oyagi

Sumitomo Mitsui Construction Co. Ltd., Shinjuku-ku, Tokyo, Japan

and

Kazuya Inoue

Disaster Prevention Research Institute, Kyoto University, Gokasho Uji, Kyoto, Japan

SYNOPSIS

Urban floods such as the ones that occurred in Fukuoka Japan in 1999 and in 2003 and the one that occurred in Seoul in 2001 induced inundation into underground space and caused extensive damage. In this paper, a mathematical model called 'storage pond model' is developed for inundation analysis in underground space. In this model, underground malls and subways are treated by the combination of multiple storage ponds, and the water volume exchange between adjacent ponds is computed by a discharge formula or momentum equation. This model was applied to the Umeda underground mall and adjacent subway spaces. Results showed that the location and the elevation of subway stations and the volume of subway spaces have major influence on the inundation water behavior in underground malls.

INTRODUCTION

In the central district of large cities, many buildings stand close together on the ground surface, under which underground space facilities such as underground malls and subways are developed. Populations and properties are densely concentrated in these places. If flood flow hits one of these areas, the flow can extend to underground space and damage can be serious. Therefore, it is very important to examine inundation flow behavior in underground space from the hydraulic and disaster preventive aspects.

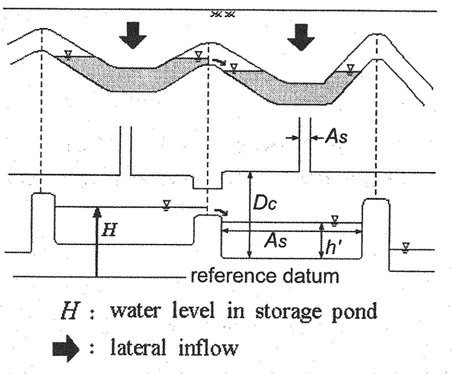

Fig.1 Storage pond model for subway

Takahashi et al. (4) first made an inundation flow model in underground space. They treated the inflow from stairs into underground space as a stepped flow. They also showed that imposing this inflow as a boundary condition, a horizontally two-dimensional inundation flow model can be applied to underground space. Inoue et al. (2) applied the above stated model to the Dojima underground mall in Osaka, Japan for the condition of overlapping of a flood and a storm surge. In these studies, only simple underground structures were treated, and the effect of ceiling in underground space was not taken into account. The authors (5) developed the underground inundation model based on the one-dimensional network model and a slot model, and applied it to the Umeda underground mall in Osaka, Japan. It was successful in treating the really complicated underground space and expressing both of the open channel flow condition and the pressurized flow condition. In their model, however, the flow behavior between the upper and lower floors and the pressurized flow condition in some places in the underground mall cannot be simulated well under some conditions of roughness coefficient, inflow discharge and slot area. In addition, many problems arose for acquisition and reduction of underground geographical data.

In view of these difficulties, a solid numerical simulation model is developed here based on a pond (tank) model that is one of the ground surface inundation models (for example, Tsurumaki et al. (7)). This model is simpler than the above stated models. In addition, the adjacent subway can be easily incorporated as the part of the underground space. The data required for the model is also reduced. This model is applied to the Umeda underground mall and adjacent subway lines and the inundation flow behavior in these areas is studied in detail.

SIMULATION METHOD

Inundation model in subway space

The inundation water which penetrates into a subway space flows down to the lower elevation part of subway line, and stays in a hollow part (convex downward). When the water level of inundation water in the hollow becomes higher than the crown of subway line (convex upward), the water overflows the crown and extends to the adjacent pond. Then, a subway space is assumed to be the space where V-shaped storage ponds with orifice on both sides are connected longitudinally (see Fig.1). The slot is also incorporated in the ceiling while at the same time considering the existence of pressurized flow condition. Thus, the dispersion of inundation water can be expressed by obtaining the discharge flowing between the adjacent storage ponds. The governing equations are the continuity equation and the discharge formula which are expressed as follows:

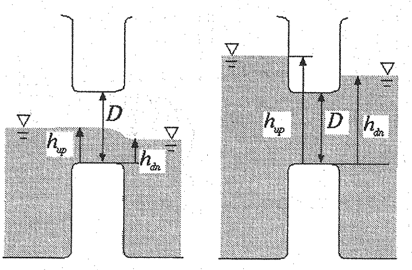

Fig.2 Flow pattern between storage ponds

(continuity equation)

$$\frac{dV}{dt} = A(H)\frac{dH}{dt} = Q_{in} - Q_{out} + Q_{ins} \quad ; \qquad A(H) = \begin{cases} A_f : h' < D_c \\ A_s : h' \geq D_c \end{cases} \tag{1}$$

where V is water volume in the storage pond, t denotes time, $A(H)$ is the area for the water level H, Q_{in} is inflow discharge from the adjacent storage pond, Q_{out} is the outflow discharge to the adjacent storage pond and Q_{ins} is the inflow discharge from exterior area such as the ground surface. h' is water depth in the storage pond, D_c is ceiling height, A_f is the area related to the storage pond shape, and A_s is the slot area.

(discharge formula)

The discharge formulas for orifice are expressed below by h_{up} and h_{dn} which indicate upstream and downstream water depths measured from the base of orifice, respectively. And D is the orifice height and B is orifice width (see Fig.2).

(i) $D \geq h_{up} \geq 0$

$$Q = \mu B h_{up}\sqrt{2gh_{up}} \quad ; \qquad \frac{h_{dn}}{h_{up}} \leq \frac{2}{3} \tag{2}$$

$$Q = \mu' B h_{dn}\sqrt{2g(h_{up} - h_{dn})} \quad ; \qquad \frac{h_{dn}}{h_{up}} > \frac{2}{3} \tag{3}$$

where μ, μ' are discharge coefficients, and g denotes gravity acceleration.

(ii) $h_{up} > D$

$$Q = \frac{2}{3}C\sqrt{2g}B\left\{h_{up}^{\frac{3}{2}} - (h_{up} - D)^{\frac{3}{2}}\right\} \quad ; \qquad h_{dn} \leq 0 \tag{4}$$

$$Q = \frac{2}{3}C\sqrt{2g}B\left\{(h_{up} - h_{dn})^{\frac{3}{2}} - (h_{up} - D)^{\frac{3}{2}}\right\} + C'Bh_{dn}\sqrt{2g(h_{up} - h_{dn})} \quad ; \qquad D \geq h_{dn} \geq 0 \tag{5}$$

$$Q = C'BD\sqrt{2g(h_{up} - h_{dn})} \quad ; \qquad h_{dn} \geq D \tag{6}$$

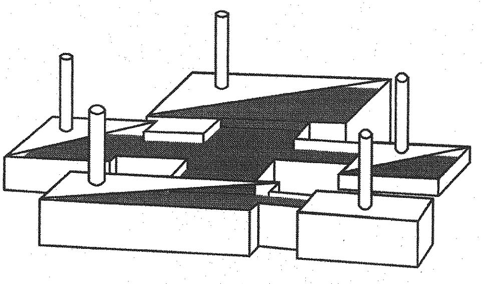

Fig.3 Storage pond model for underground mall

where C, C' are discharge coefficients. The above formulas are referred in JSCE (Ed.) (3) and Tsubaki and Araki (6).

Inundation model in underground shopping mall

Underground shopping malls are generally composed of stores, open spaces, subway entrances and basements of adjacent buildings. Though the total underground mall may be very complicated, it can be divided into distinct parts. If each part is assumed to be a storage pond that has its own volume, the underground mall is expressed by the combination of storage ponds in the three dimensions (see Fig.3). The slot is also incorporated in each pond taking into account the pressurized flow condition. Thus, the dispersion of inundation water can be expressed by obtaining the discharge flowing between the adjacent storage ponds, similarly with the subway space. The governing equations are the continuity equation and the momentum equation expressed below as follows:
(continuity equation)

Considering the water continuity in the storage pond,

$$A\frac{dH}{dt} = \sum Q_i + Q_{ins} \quad ; \qquad A = \begin{cases} A_f : h < D \\ A_s : h \geq D \end{cases} \tag{7}$$

where A is the effective base area of storage pond, H is water stage, Q_i is inflow discharge from i-th adjacent storage pond and Q_{ins} is lateral inflow discharge from the ground surface. h is water depth and D is the ceiling height of the storage pond. The treatment of A is similar to the case of the subway space:
(momentum equation)

Considering the water behavior between the adjacent storage ponds, the following equation is applied:

$$\frac{L}{gA_b}\frac{dQ}{dt} = \Delta H - \alpha LQ|Q| \tag{8}$$

where ΔH is the water level difference between the adjacent storage ponds, Q is discharge, and L is the distance between the base area centroids of adjacent storage ponds. A_b is the cross-sectional area of adjacent storage ponds, and it is determined according to the water depths in the adjacent storage ponds.

$$A_b = B_b \frac{\min(h_i, D_i) + \min(h_j, D_j)}{2} \tag{9}$$

where i and j show the adjacent storage ponds and B_b is the width of border plane of adjacent storage ponds. α is loss coefficient associated with Manning coefficient, n, and is expressed as follows:

$$\alpha = \frac{n^2 s^{4/3}}{A_b^{10/3}} \tag{10}$$

where s is the wetted perimeter of the border plane. s is expressed as follows, considering the perfect pressurized flow condition and other conditions,

$$s = B' + 2\frac{\min(h_i, D_i) + \min(h_j, D_j)}{2} \quad ; \qquad B' = \begin{cases} 2B_b : h_i \geq D_i, \quad h_j \geq D_j \\ B_b : \quad otherwise \end{cases} \tag{11}$$

At the inflow position from the ground surface to the underground mall and the dropping position from the upper floor to the lower floor in multistory underground mall, the following step flow formula is applied (Inoue et al.(2)),

$$Q = B_e \mu_0 h_e \sqrt{g h_e} \tag{12}$$

where, B_e is effective width of entrance, μ_0 is discharge coefficient and h_e is the water depth in the upper storage pond. If the lower storage pond is pressurized, then Eq. 8 is applied.

APPLICATION TO UMEDA UNDERGROUND SPACE

Umeda underground space

The underground inundation flow model based on the storage pond model is applied to the Umeda underground shopping mall and adjacent subway lines (Midousuji-line, Tanimachi-line, Yotsubashi-line, JR

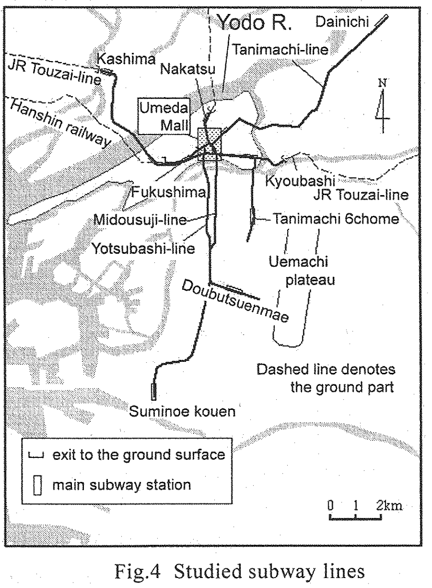

Fig.4 Studied subway lines

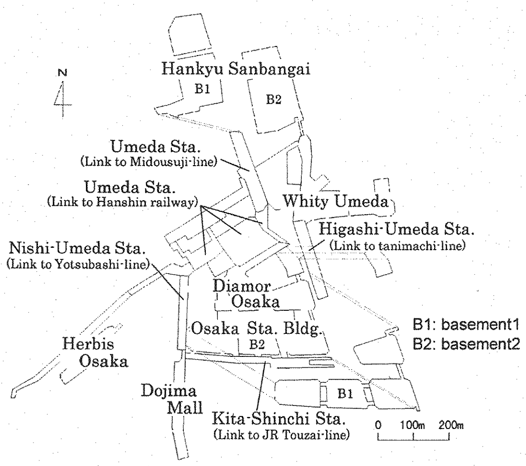

Fig.5 Studied underground mall

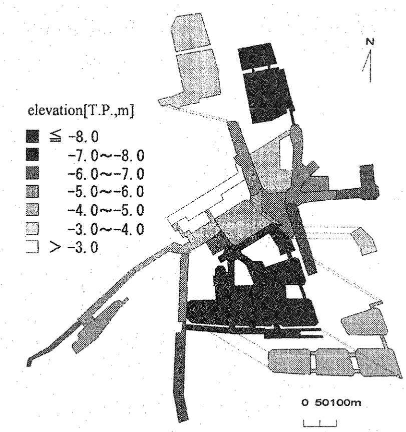

Fig.6 Elevation of underground mall

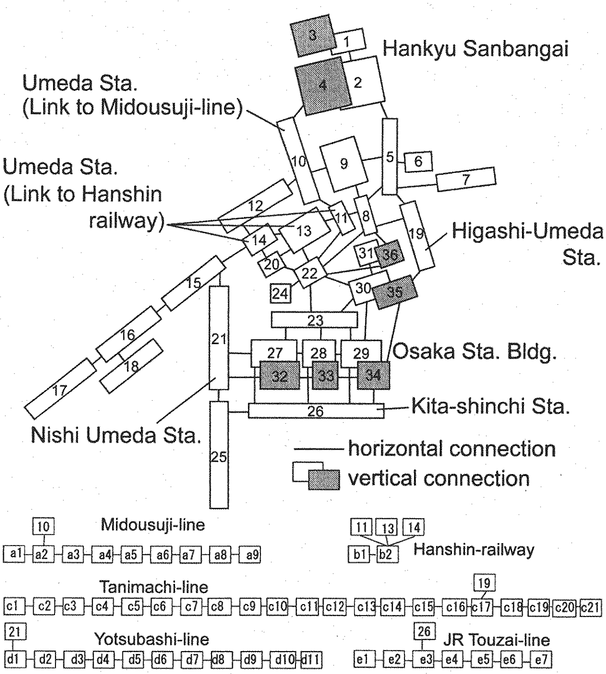

Fig.7 Connection of storage ponds

Touzai-line and Hanshin railway). The studied section of each subway line is shown in Fig.4. The studied section is limited to the location of the exits to ground surface or to the areas where the ground elevation level is the same as that of the Yodo river bank crown. The reason for this is that even if inundation occurs in Osaka city area by the bank breach of the Yodo River, the inundation water would not exceed the bank crown elevation.

The studied subway section is divided into some V-shaped storage ponds. The ceiling heights of stations and others are set at 5.5m and 5.0m, respectively. The ratio of the slot area to the total underground base area is set at 0.02. This value is estimated based on the area of stairs connecting to the ground surface.

Fig.5 shows the studied area of Umeda underground and Fig.6 shows its elevation distribution. The connection points to subways are seen in Fig.5. Fig.7 shows the structure of storage ponds for the Umeda

Table 1 Volume of underground space

	volume $\times 10^3 (m^3)$
Umeda mall	650
Midousuji-line	710
Tanimachi-line	1192
Yotsubashi-line	739
JR Touzai-line	751
Hanshin railway	102

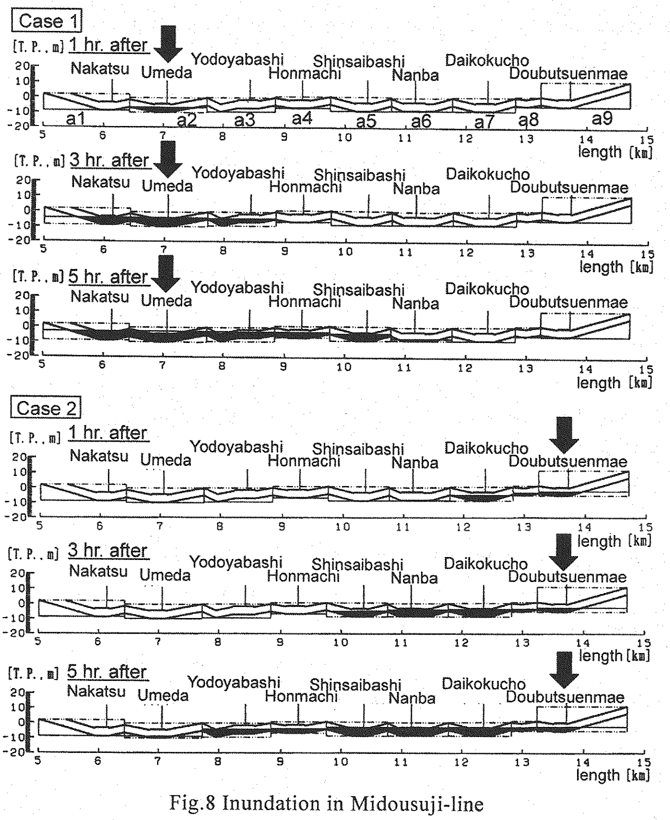

Fig.8 Inundation in Midousuji-line

underground mall and adjacent subway lines. Each number indicates the storage pond used for computation. The number with alphabet shows the storage pond of subway lines.

The slot ratio is assumed to be the same as that of subway. The ceiling height and effective base area of each storage pond are determined based on the geographical information data and field surveys. Table 1 shows the volume of the Umeda underground mall and each subway line.

Simulation results and discussions

First, the subway Midousuji-line is selected, and the inundation process is studied. The studied subway section is about 9.7km, and the section is divided into 9 storage ponds with V shape. The constant discharge of $20m^3/s$ is assumed to flow into the storage pond including Umeda station (Case 1) and the storage pond including Doubutsuenmae station (Case 2), respectively. The computational time step, Δt, is 0.05s. The discharge coefficients adopted here are μ=0.35, μ'=0.91, μ_0=0.54, C=0.61, and C'=0.55. These values are within the standard range (Inoue (1)) and sensitivity analysis for these parameters is not executed here. Fig.8 shows the temporal change of inundation situation of Case 1 and Case 2. The inflow starting time is set as the computation starting time. In Case 1, Nakatsu and Yodoyabashi stations are not inundated within an hour, while, in Case 2, the inundation water expands to Daikokucho station. Similarly, in Case 1, the inundation proceeds to Nanba station only at 5hr., while, in Case 2, the inundation expands to Umeda station. And, in Case 2, the inundation depth at Daikokucho station becomes higher than that at Doubutsuenmae station within an hour. The inundation process varies greatly according to inflow positions, influenced by the longitudinal geographical condition of subway line. Namely, the elevation of each storage pond and its connection has much influence on the inundation process in the subway space.

Next, the inundation in the underground mall with adjacent subways is discussed. The inundation by overflow from the large river is assumed. The constant inundation water intrusion into underground space through some entrances is assumed, and the two kinds of entrance conditions are imposed. In Case A, the discharge of $15m^3/s$ flows into each pond of No.3, 4, 5 and 7 in Fig.7, located in the northern part of underground mall, while, in Case B, the discharge of $30m^3/s$ flows into the ponds of No.25 and 26 in Fig.7, in the southern part. The total inflow discharge is $60m^3/s$ for both cases. The Manning coefficient n is set as 0.10 for the sections between upper and lower floors and 0.03 for the horizontal planes. Both of these values consider the form of irregularity.

First, the inundation water behavior of Case A is discussed. Fig.9 shows the temporal change of inundation in the underground mall. The time shown here denotes the time elapsed from the underground inflow start. At 1hr., the inundation water flows down to the low elevation area, and the inundation area expands widely to Hankyu-Sanbangai, Whity Umeda, Diamor Osaka and B2 (basement 2) of Osaka Station Building. At B2 of Hankyu-Sanbangai (ponds of No.1, 2 in Fig.7), the inundation depth exceeds 2m. Fig.10 shows the temporal change of inundation in the subway Tanimachi-line. In this case, the intrusion into Tanimachi-line is greater compared with other lines. Within an hour, the inundation occurs from Higashi-Umeda station (pond of No.19 in Fig.7). After that, the inundation depths almost keep constant in the underground mall until 4hr., while, the inundation section expands in Tanimachi-line, and at 4hr., the inundation water reaches the north of Moriguchi station, about 10km apart from Umeda area. After Tanimachi-line is filled with water, the inundation water disperses again in the underground mall, and within six hours, the inundation depths increase in Diamor Osaka area and B2 of Osaka Station Building further.

Next, the inundation water behavior of Case B is discussed. Fig.11 and Fig.12 show the temporal change of inundation in underground mall and inundation in JR Touzai-line, respectively. The inundation water intruding into the ponds of No.25 and 26 in Fig.7 flows down to Diamor Osaka, B2 of Osaka Station Building and JR Touzai line copiously. The elevations of these parts are comparatively low. Within an hour, the inundation depth exceeds 1m at B2 of Osaka Station Building. The inundation area does not expand so much during the first two hours. As for the subway lines, inundation water intrudes into JR Touzai-line only. Within four hours, all the area of Diamor Osaka is inundated and JR Touzai-line is almost submerged. After this subway line is filled with water, the inundation water disperses in the underground mall. And at 6hr., the inundation area expands to Hankyu-Sanbangai, Whity Umeda and Herbis Osaka (ponds of No.15, 16 in Fig.7).

The above findings under the simple but different conditions provide evidence that the inundation in underground depends to a great extent on the location of inflow entrances. It should be noted that this is caused by the complicated structure of underground mall and the existence of subway space. The location and elevation of the subway station and the volume of subway space have a major influence on the expansion condition of inundation water.

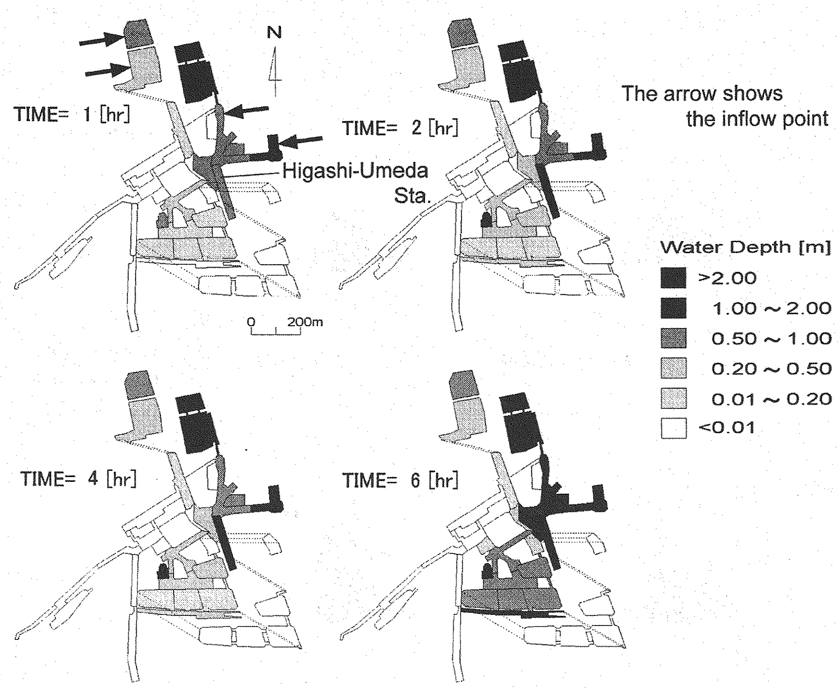

Fig.9 Inundation in underground mall (Case A)

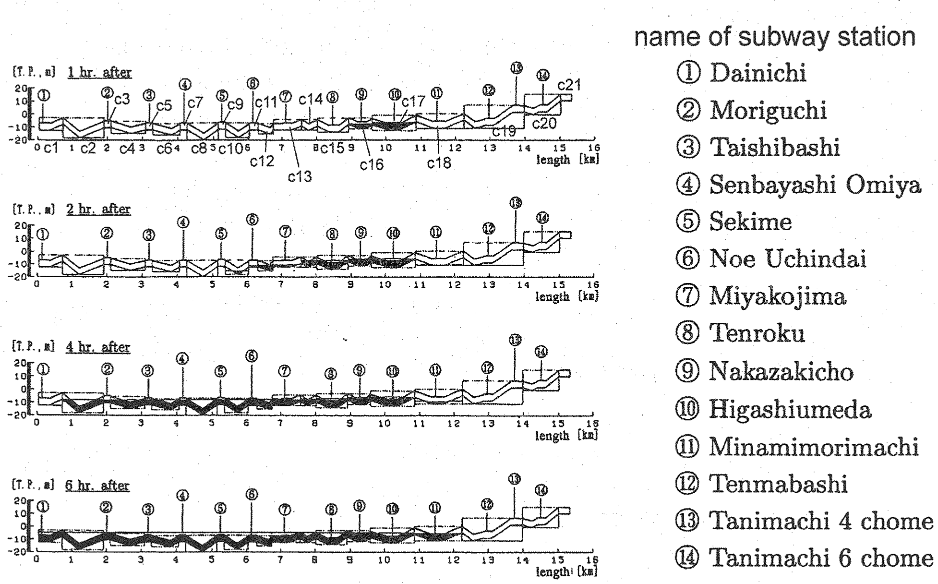

Fig.10 Inundation in Taninmachi-line (Case A)

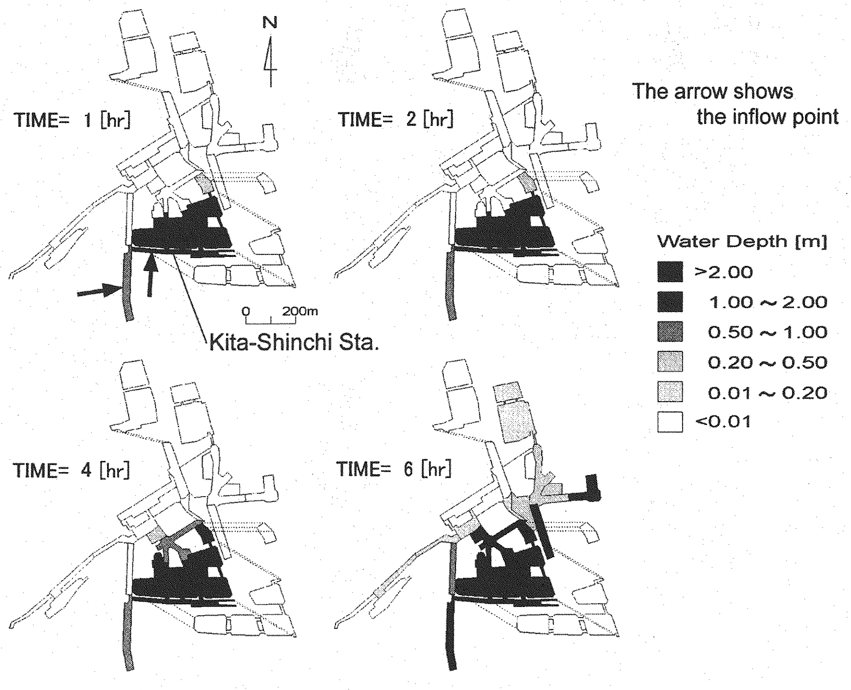

Fig.11 Inundation in underground mall (Case B)

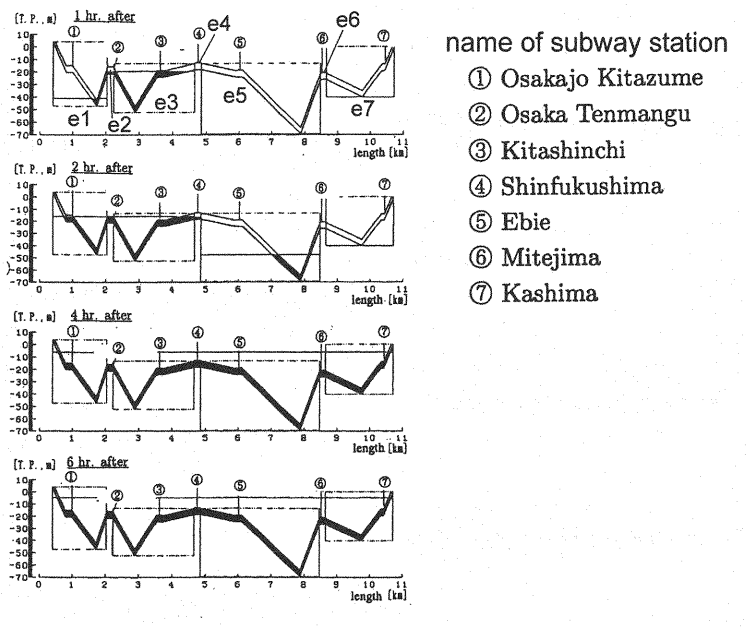

Fig.12 Inundation in JR Touzai-line (Case B)

CONCLUDING REMARKS

The main results obtained through this study are as follows.

(1) A mathematical model based on the storage pond model was developed and applied to Umeda underground mall and the adjacent subways. The model developed here can be applied to real convoluted underground spaces without much difficulty of data set preparation.

(2) It was found that the location and elevation of subway station and the volume of subway space have a major influence on the inundation water behavior in complicated underground malls connected with subway lines.

The problems to be solved in the future are as follows.

(1) The validity of simulation model developed here needs to be verified. Therefore, a hydraulic model test of underground space is required to obtain the data for calibration.

(2) After the validity of the model is confirmed, the simultaneous computation of the ground and underground inundation should be successfully executed from the aspect of urban flood disaster prevention.

REFERENCES

1. Inoue, K. : Study on numerical simulation method of unsteady open channel flow and its application to hydraulics, Doctoral thesis of Kyoto University , p.128, p.177, 1986 (in Japanese).
2. Inoue, K., Nakagawa, H., Toda, K. and Mizota, T. : Analysis of overland flood flow intrusion into underground space, Proc. of the Symposium on Underground Space, Vol.2, JSCE, pp.95-102, 1997 (in Japanese).
3. JSCE (Ed.): Hydraulic Formula Book, JSCE, p.265, 1971 (in Japanese).
4. Takahashi,T., Nakagawa, H. and Nomura, I. : Simulation method on inundation in an underground space due to intrusion of overland flood flows, the Annuals of the Disaster Prevention Research Institute, Kyoto University, No.33, B-2, pp.427-442, 1990 (in Japanese).
5. Toda, K., Inoue, K., Maeda, O. and Tanino, T. : Analysis of overland flood flow intrusion into underground space in urban area, Journal of Hydroscience and Hydraulic Engineering, Vol.18, No.2, JSCE, pp.43-54, 2000.
6. Tsubaki, T. and Araki, M.: Exercise of Hydraulics (1), Morikita Press, pp.204-207, 1961 (in Japanese).
7. Tsurumaki, Y., Okuda, A. and Kouzuki, R. : On the modeling of the spread of the flood flow using bi-dimensional tank model method, Proc. of the 25th Japanese Conference of Hydraulics, JSCE, pp.249-256, 1981 (in Japanese).

APPENDIX - NOTATION

The following symbols are used in this paper:

A =storage pond area;

A_b =cross-sectional area of adjacent storage ponds;

A_f =area related to the storage pond shape;

A_s =slot area;

B =orifice width;

B_b =width of border plane of adjacent storage ponds;

B_e =effective width of entrance;

C, C' =discharge coefficients;

D =orifice height;

D_c =ceiling height;

g =gravity acceleration;

h, h' =water depths in the storage pond;

h_{dn} =downstream water depth measured from the base of orifice;

h_e =water depth in the upper storage pond;

h_{up} =upstream water depth measured from the base of orifice;

H =water stage;

L =distance between the base area centroids of adjacent storage ponds;

n =Manning coefficient of roughness;

Q =discharge;

Q_i =inflow discharge from i-th adjacent storage pond;

Q_{in} =inflow discharge from the adjacent storage pond;

Q_{ins} =inflow discharge from exterior area such as the ground surface;

Q_{out} =outflow discharge to the adjacent storage pond;

s =wetted perimeter of the border plane;

t =time;

V =water volume in the storage pond;

α =loss coefficient;

μ, μ', μ_0 =discharge coefficients;

ΔH =water level difference between the adjacent storage ponds; and

Δt =computational time step.

(Received August 18, 2003 ; revised June 2, 2004)