Journal of Hydroscience and Hydraulic Engineering
Vol. 18, No.2 November, 2000, 43-54

ANALYSIS OF OVERLAND FLOOD FLOW INTRUSION INTO UNDERGROUND SPACE IN URBAN AREA

By

K. Toda
Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan

K. Inoue
Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan

O. Maeda
Tokyo Electric Power Company, Numata, Gunma, Japan

and

T. Tanino
Japan Highway Public Corporation, Takamatsu, Kagawa, Japan

SYNOPSIS

Most of large cities in Japan face the potential danger of flood disaster due to river flood and/or storm surge. This paper treats a numerical analysis of overland flood flows in an urban area with underground space, especially aiming at the inundation flow behavior in underground space. A one-dimensional network mathematical model to express inundation flow in underground space liked with a two-dimensional overland flood flows by river bank break is developed and applied to "Umeda" district in Osaka city, Japan. For the pressurized flow condition in underground space, a slot model is also applied. The obtained results show that the model developed here can simulate the aspects of inundation flow into underground space fairly well.

INTRODUCTION

Most of large cities in Japan are located in the coastal zone which is an alluvial plain of river mouth, and they face the potential danger of flood disaster due to river flood and/or storm surge. In addition, they also have the danger of urban flood due to heavy rain by the existence of high surrounding levee for river protection. While in the central district of large cities, a number of buildings stand close together on the land surface, under which underground space facilities such as underground mall and subway are developed. Populations and properties are densely concentrated there. If this area is attacked by overland flood flow due to bank break, the flow would extend to underground space, and the damage would be serious. Therefore, it is very significant to predict the flood disaster, especially the inundation flow behavior accurately from the hydraulic and disaster preventive aspects. In view of this situation, this paper treats a numerical simulation method of overland flood flows in urban area with underground space, and especially aims at development of inundation flow modeling in underground space.

Takahashi et al.(8) first studied inundation flow modeling in underground space. They treated the inundation flow from stairs into the underground space as a stepped flow. Imposing this inflow as a boundary condition, they also showed that a horizontally two-dimensional inundation flow model can be applied to underground space. Inoue et al.(4) applied the above mentioned model to Dojima underground mall, Osaka, Japan and discussed the effects of flash-board of stairs entrance and draining pumps. In these studies, however, the underground spaces were very simple ones and applicability of the model to real complicated underground space has not been discussed. Also in the previous studies, the ceiling of the underground space was not taken into account, therefore, the pressurized flow condition could not be well expressed.

In order to solve these problems, a one-dimensional network model including a slot model to express inundation flow in underground space linked with a two-dimensional overland flood flows on the surface land is developed here and applied to a real underground space.

STUDIED AREA

The model developed here is applied to "Umeda" district in Osaka city, Japan. The reasons why this area was chosen as the studied area are as follows,

(1) This area belongs to the central business district in the north of Osaka city, and is very important from the viewpoint of flood disaster prevention,

(2) This area is located near the Yodo river, which is one of the largest rivers in Japan, and has the high potential of suffering flood hazard,

(3) This area has its large underground mall space whose shape is so complicated that inundation flow analysis there is worth studying.

The studied surface area is the northern part of Osaka city which is surrounded by the Yodo river, the Dojima river and the Oh river (see Fig. 1). The studied underground space, "Umeda" underground mall whose location is also shown in Fig. 1, is illustrated in Fig. 2.1, which comprises several underground malls, subway stations and underground floors of buildings adjacent to them. In Japan, underground mall tends to be a complicated structure for the effective use of limited underground space. The structure of "Umeda" underground mall is expressed in Fig. 2.2. From the basement 1, some pathways extend to the upper and lower floor of the adjacent mall, and others are liked with subway stations which are located at the lower floor corresponding to the basement 2. This complicated network comprising multi-stories is the important point of "Umeda" underground area. The network used in the computation is also shown in Fig. 3.

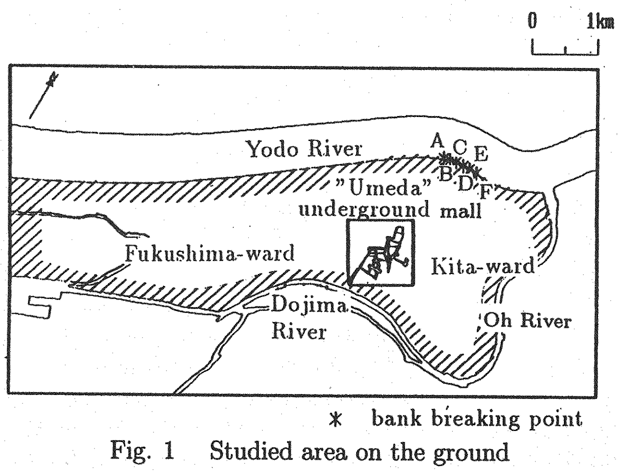

Fig. 1 Studied area on the ground

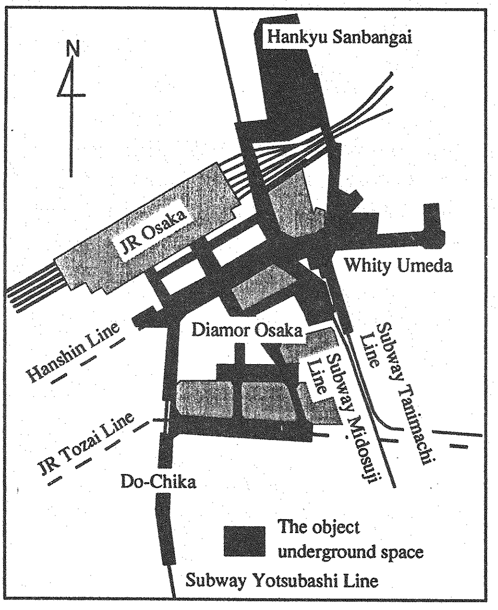

Fig. 2.1 Studied area in the underground space

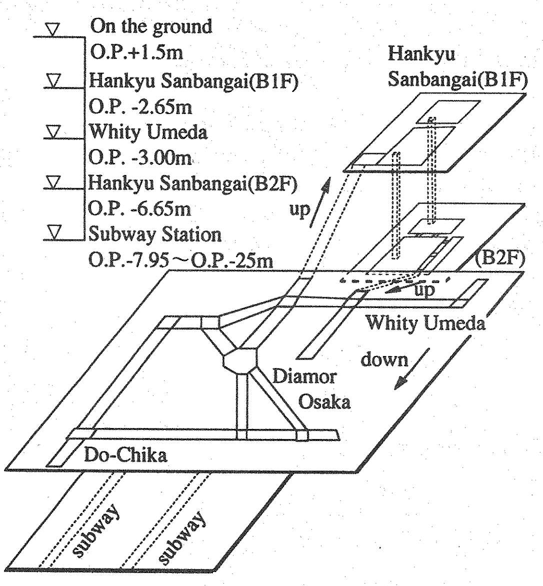

Fig. 2.2 Structure of underground space

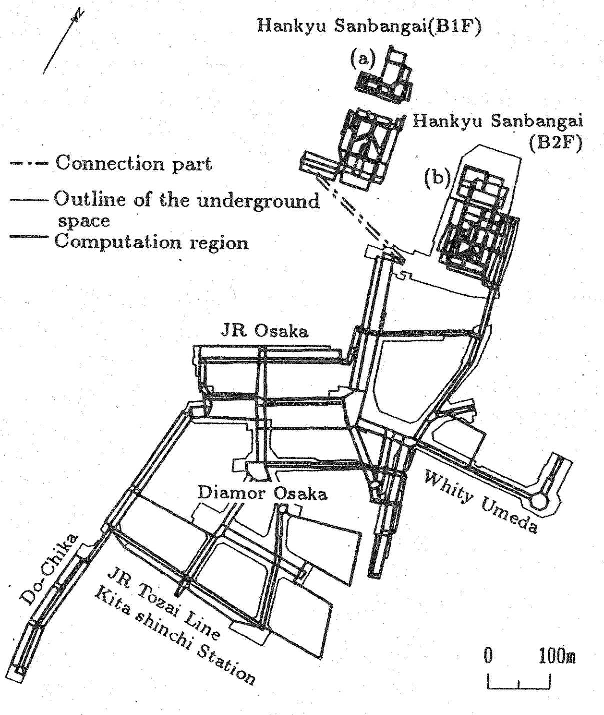

Fig. 3 Computation region in the underground

NUMERICAL SIMULATION METHOD

Inundation Flow Simulation on the Ground

An unsteady overland flood flow resulting from bank break into a flood plain area can be analyzed by a horizontally two-dimensional model, which comprises continuity equation, and x- and y- components of momentum equations. The studied area is both the river and the flood plain area. As the water depth of inundation flow is relatively small, the following shallow water equations can be applied according to Iwasa and Inoue(6).

Continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=-\frac{Q}{\Delta x \Delta y} \tag{1}$$

Momentum equation in the x direction

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_{bx}}{\rho_w} \tag{2}$$

Momentum equation in the y direction

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_{by}}{\rho_w} \tag{3}$$

in which t is time and (x,y) are Cartesian coordinates. (u,v) are velocity in the (x,y) directions, h is water depth, Q is discharge from the inundation area on the ground into underground, $\Delta x, \Delta y$ are the grid size in the (x,y) directions, respectively, (M,N) are discharge flux ($M = uh, N = vh$), and H is water stage from reference datum. (τ_{bx}, τ_{by}) are bottom shear stresses in the (x,y) directions, g is gravitational acceleration and ρ_w is density of water. The bottom shear stresses can be expressed by

$$\tau_{bx}=\frac{\rho_w g n^2 u\sqrt{u^2+v^2}}{h^{1/3}}, \quad \tau_{by}=\frac{\rho_w g n^2 v\sqrt{u^2+v^2}}{h^{1/3}} \tag{4}$$

where n is the Manning coefficient. In this paper, n=0.03 was used for the river and n=0.067 for the inundation area considering the effect of structures in the urban area.

As for the overflow discharge due to the bank break, it is estimated by the following method proposed by Iwasa and Inoue (7). Assuming that H_r is the water level of the river, H_o is the crest level of bank and H_f is the water level of the inundation area, and that $h_1 = H_r - H_o$ and $h_2 = H_f - H_o$, when $H_r > H_f$, the overflow discharge Q_o can be given by the following equations,

$$\begin{aligned} h_2/h_1 \le 2/3 \qquad & Q_o = \mu L h_1 \sqrt{2gh_1}, \\ h_2/h_1 > 2/3 \qquad & Q_o = \mu' L h_2 \sqrt{2g(h_1 - h_2)} \end{aligned} \tag{5}$$

where μ and μ' are coefficients of perfect overflow and submerged overflow, and in the case of a rectangular shaped bank break, their values are 0.35 and 0.91, respectively (2), and L is the length of bank break. In the case $H_r < H_f$, overflow occurs from the inundation area to the river. As for the discharge flowing over the steps of stairs into the underground, it is estimated by the following equation by Takahashi et al.(8),

$$Q = B_1 \mu_0 h \sqrt{gh} \tag{6}$$

where h is the water depth on the ground, B_1 is the effective length of stairs and μ_0 is the discharge coefficient. According to them, the value of μ_0 is nearly $0.8 \sim 1.0$, and $\mu_0 = 0.91$ was used here.

The Leap-frog method, an explicit method, was used for discretization of the above equations. The forward-difference scheme and 1st-order up-wind difference scheme were applied to the time-dependent terms and advection terms, respectively, and for the other terms the centered-difference scheme was used. For treatment of the bottom shear stress terms, a semi-infinite method was used to avoid the Vasiliev instability (5).

Inundation Flow Simulation in Underground Space

(a) Inundation flow modeling

Generally, underground mall in urban area comprises pathways, stores and connecting parts to the upper and lower floors. In "Umeda" district treated in this paper, pathways form a network, and stores including department stores are located in both sides of them. Also, stairs and escalators connecting a floor with the upper and the lower one are placed at the intersections of pathways. The pathway width is at most 10m and there is no elevation difference in the transverse direction. The above characteristics indicate that inundation flow is considered to go down longitudinally along pathways which form a network. Therefore, the model can be made that a pathway is a link, an intersection is a node and an area including stores and buildings is a block, and an underground mall area is expressed by a network comprising them (see Fig. 4). Assuming that links denoting underground pathways are divided into some grids and the width is constant over one link, inundation flow in underground space can be modeled as a one-dimensional unsteady flow according to Inoue et al (3).

As the underground pathway is about 3m in height, co-existence of free-surface flow condition and pressurized flow one has to be taken into account. In treating this, a slot model (1) has been applied here. In this technique, a very narrow slot is assumed at the pathway ceiling such that this slot does not increase either the cross-sectional area or the hydraulic radius of the pressurized pathway. Schematic view of the assumed slot is shown in Fig. 5. Thus, the free-surface and the pressurized flows do not have to be analyzed separately. Once the pathway is primed, then the depth is replaced by the piezometric head acting on the pathway walls at that location. The basic equations in links can be expressed as follows,

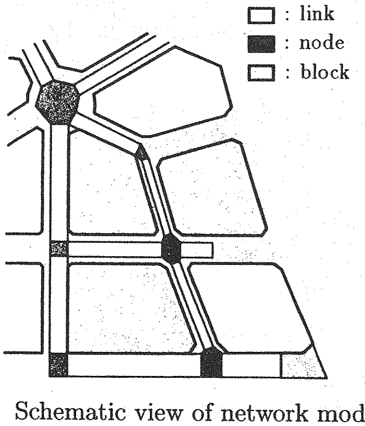

Fig. 4 Schematic view of network model

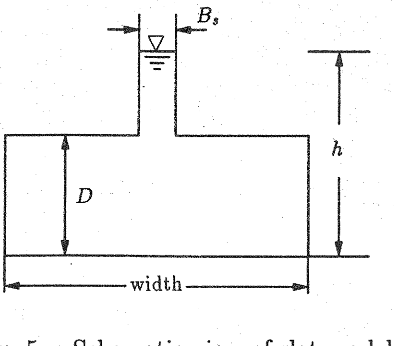

Fig. 5 Schematic view of slot model

continuity equation

$$\frac{\partial h}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = \frac{q}{\Delta x_l} \qquad B = B_0(h < D), \quad B = B_s(h \geq D) \tag{7}$$

momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial uQ}{\partial x} = -gA\frac{\partial H}{\partial x} - gn^2\frac{|Q|Q}{R^{4/3}A} \tag{8}$$

where h is depth (piezometric head), u is velocity, Q is discharge, H is water stage from reference datum, q is lateral inflow discharge, Δx_l is the mesh size of link, A is cross-sectional area and R is hydraulic radius. B_0 is the pathway width and B_s is the assumed slot width and is estimated by the following equation,

$$B_s = \frac{gA_0}{a^2} \tag{9}$$

where A_0 is the cross-sectional area and a, which is originally formulated as the waterhammer velocity, only means a hydraulic parameter for expressing the pressurized flow here.

In the boundary of link, namely in the connection of link and node or block, the momentum equation is expressed as follows by neglecting the non-linear convective term,

$$\frac{\partial Q}{\partial t} = -gA_b\frac{DH}{DX} - gn^2\frac{|Q|Q}{h_b^{4/3}A_b} \tag{10}$$

where h_b and A_b are the water depth and the area at the border plane, respectively, DH is the water level difference and DX is the distance between the center of the adjacent link and node or block. DX is defined as follows (see Fig. 6),

In the case of link and node, $DX = DN + \Delta x_l/2$
In the case of link and block, $DX = DJ + B/2$
where B is the link width, DN and DJ denote the shortest distance from the border plane to the center of node and block, respectively. h_b and A_b can be expressed as follows,

In the case of link and node,

$$h_b = \frac{DN \times h_l + \Delta x_l/2 \times h_n}{DX}, \qquad A_b = B \times h_b$$

In the case of link and block,

$$h_b = \frac{DJ \times h_l + B/2 \times h_j}{DX}, \qquad A_b = \Delta x_l \times h_b$$

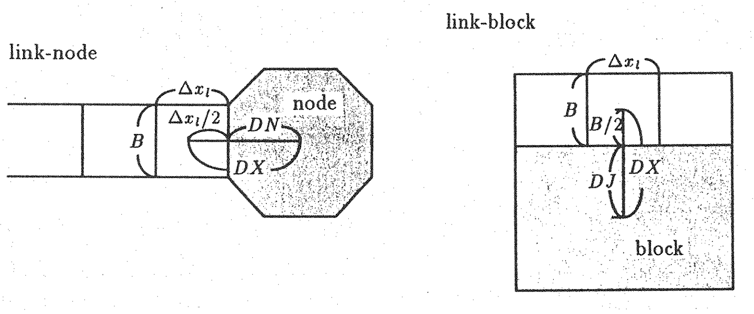

Fig. 6 Treatment of border of link

in which h_l, h_n and h_j denote the depth of link, node and block, respectively. The similar methods can be applied to the boundary treatment of node and block. The continuity equation at node and block is treated based on the discharge going in and out as follows,

$$\frac{\partial h}{\partial t} = \frac{1}{A}\sum_{i=1}^{m} Q_i \tag{11}$$

$$A = A_p(h < D_c) \qquad A = A_s(h \geq D_c)$$

where m is the number of border planes, A_p is the plane area of node or block, and D_c denotes the ceiling height. A_s is estimated by

$$A_s = \sum_{i=1}^{m} B_{sd_i} DL_i \tag{12}$$

where B_{sd_i} is the slot width of the border plane and DL_i is the distance between the border plane and the centroid of node or block.

(b) Boundary treatment

The boundary condition that the inundation flow goes down from the surface area into the underground space is expressed by use of eq. 6. The discharge into the underground space in each grid on the surface is computed and distributed to the corresponding node in the underground network. Outflow from the underground space is expressed by the discharge into a subway station. Subway gates are placed in blocks and the outflow discharge is calculated by eq. 6 based on the depth in the block. The discharge from the upper to the lower floor is evaluated similarly by that from the upper block to the lower node. Subway stations located at the lowest floor are treated as pools, where discharge from the underground mall space is stored only. The inundation flow propagation along subway railroad is not taken into account here.

APPLICATION OF THE MODEL TO UMEDA DISTRICT

Computation Condition

With regard to the inundation flow computation on the ground, Δx=Δy=100m was used, and the studied area was divided into 90 and 50 in the x and y direction, respectively. The bank break of the Yodo river was assumed. At the upstream end of the river, the assumed flood hydrograph in Fig. 7 was imposed as the boundary condition. The peak value is the design flood discharge of the Yodo river. At the downstream end of the river, the discharge was assumed to flow out according to the discharge formula for drop. Computational time Δt was 5 seconds, the total computed time was 9 hours, and the bank breaking time was set 3 hours after the computation start. Here, the starting time of computation, the bank breaking time and the finishing time of computation were defined by -3.0 hr., 0.0 hr. and 6.0 hr., respectively. As for the bank breaking points, A $\sim$ F at 100m intervals in Fig.

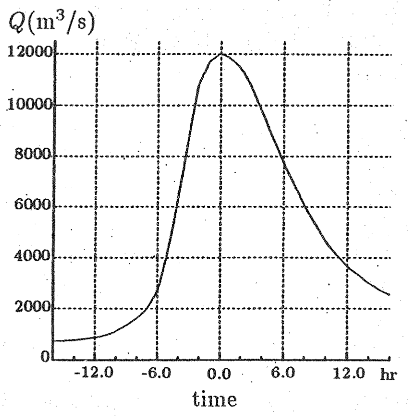

Fig. 7 Assumed flood hydrograph

1 were chosen such that much inundation flow would go into "Umeda" underground mall. The rectangular shaped bank breaking condition such that the width was 100m and the height was 3m higher than the flood plain area elevation was assumed. As for the discharge into underground space, it was evaluated by eq. 6 in the meshes including the stairs to the underground space.

Next, with regard to the inundation flow computation in the underground, the inflow discharge to the underground was allotted to the nearest node as the boundary condition. As for the inundation flow from the upper floor to the lower one, it was treated as the discharge from the block in the upper floor to the node in the lower one, both of which are the nearest to the stairs. The discharge was also computed by eq. 6. The total computed time was 5.5 hours from 0.5 hr. to 6.0 hr. and Δt was 0.05 sec. The divided mesh size of link was set nearly Δx_l = 3m. The width was constant over one link and the ceiling height in link and node was set 3m, but, for the node including the stairs, their height was taken into account.

As for the values of a in eq. 9, a=20-50m/s is commonly used in the application to sewerage systems as is pointed out by Watanabe et al (9). Some preliminary computations were executed by changing a. As the results, it was found that this method became unstable in this study case when a was larger than 50m/s, and even if a was smaller than 50m/s, the computational results were very sensitive to a. After some trials, a=10m/s was finally adopted from the condition that the piezometric head was continuous between the adjacent upper and lower floors in the case of pressurized flow. The rational method for determining a is the remaining significant task.

Computational Results and Discussion

The computations with different bank breaking points were executed. Fig. 8 shows the total inundating water volume, the inundating water volume on the ground and that into the underground for 6 hours from 0.0 hr. to 6.0 hr. From this figure, it is expected that if the bank breaks at the west of point A, inflow discharge into the underground would decrease more. Also, in the case that it breaks at east of point B, the total inundating water volume takes its maximum value at point C and it decreases slightly as the breaking point goes to the east and this tendency would be the same for the east of point F. From the above results, it is considered that the breaking point C causes the maximum inundation flow discharge. Therefore the breaking point C was used for the analysis below.

Fig. 9 shows the temporal change of inundation flow depth distribution on the surface. After 1.0 hr., the zone where inundation flow depth is more than 1.5m extends from the bank breaking point to the south direction, which reaches the north end of the underground mall. The maximum inflow discharge into the underground occurs at 2.0 hr.

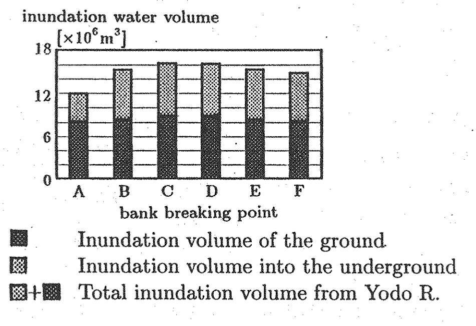

Fig. 8 Inundation water volume for 6 hours

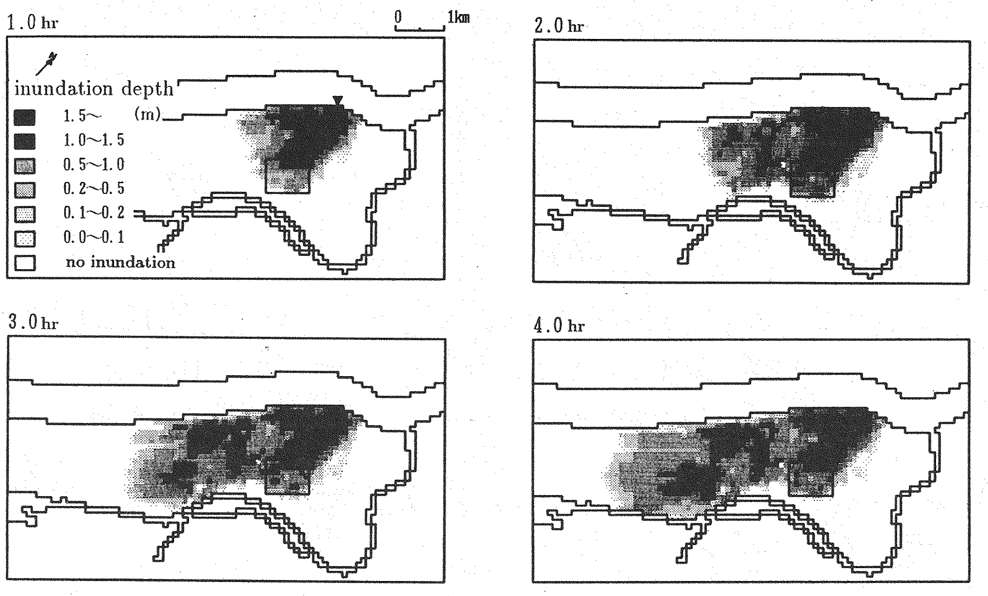

Fig. 9 Computational results on the ground (temporal change)

Fig. 10 shows the simulation results at 1.0 hr. and 2.0 hr in the underground space. Fig. 11 shows the temporal change of inundation flow depths at several points there. By considering the ceiling height, the condition of basement 2 of Hankyu Sanbangai (the mall H) influences to basement 1, where the inundation flow depth increases. The temporal change of the inundation flow depth at the two locations of basement 1 and 2 of the mall H (locations (a) and (b)) is seen in Fig. 11. At time 1.0 hr., the inundation flow depth at (b) becomes 3m, and the flow changes to the pressurized one. Immediately after the pressurized condition at (b), the depth at (a) increases rapidly. As a reference, the simulation results obtained by assuming the free-surface condition only are also shown in Fig. 11, which are different from those by assuming both the free-surface condition and the pressurized condition in the locations (a) and (b). Except for the mall H, the inundation flow does not reach the ceiling, but after 1.0 hr., the inundation flow depth increases rapidly and it has the maximum value of more than 1.5m. Also the depth does not change so much between 1.5 hr. and 6.0 hr.

The above results show that the volume of underground space considered here is not so large compared with the volume of inundation water which flows into the flood plain area from the Yodo river and the increase of inundation water depth in the underground space is very rapid. Therefore, warning system and quick evacuation are very significant to flood disaster prevention in underground space.

CONCLUDING REMARKS

In treating the inundation flow behavior in an urban area with underground space, a one-dimensional network mathematical model to express inundation flow in underground space linked with a two-dimensional overland flood flow model was developed. The model was applied to "Umeda" district in Osaka city, Japan, which has a complicated multi-layered underground space. The obtained results have clarified that the model developed here can simulate the aspects of inundation flow into underground space qualitatively. The remaining task is improvement of the slot model in the complicated network for high accuracy.

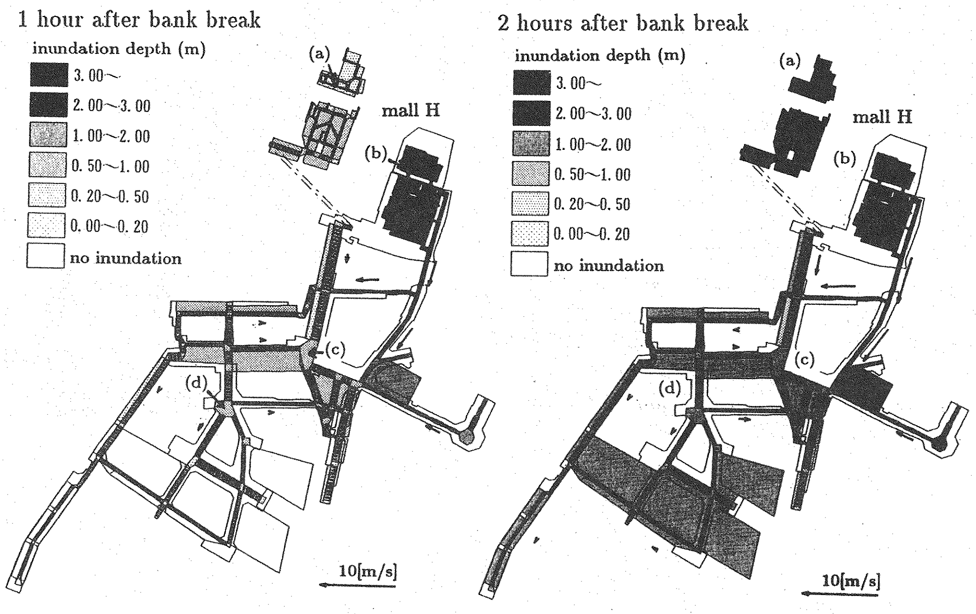

Fig. 10 Computational results in the underground space

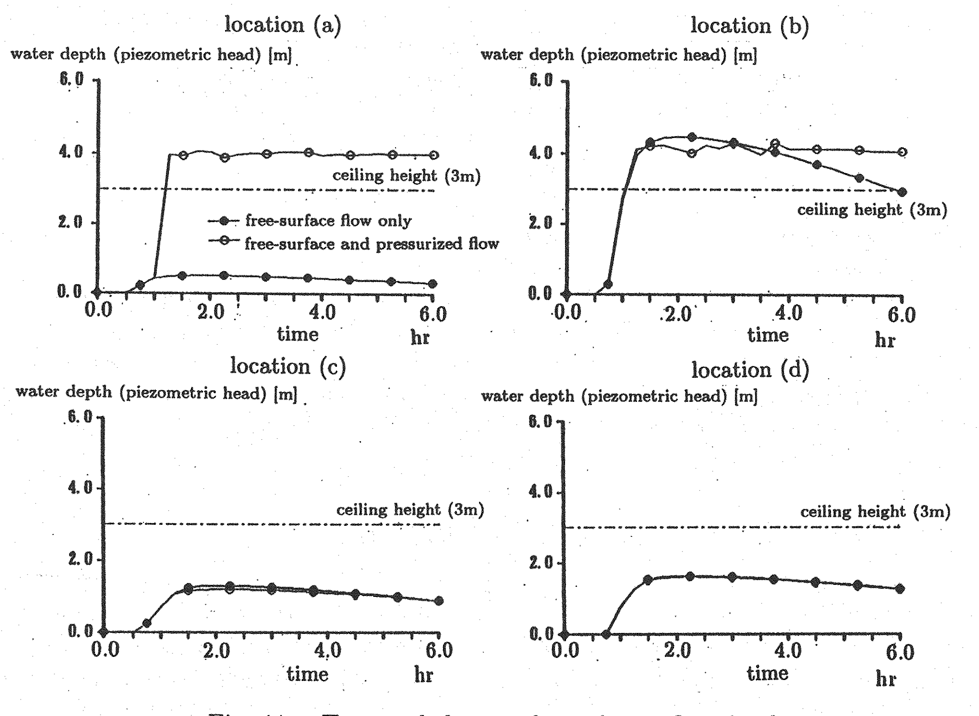

Fig. 11 Temporal change of inundation flow depth

REFERENCES

1. Chaudhry, M.H. : Applied Hydraulic Transients, Van Nostrand Reinhold, pp.422-423, 1979.

2. Inoue, K. : Study of numerical computational method of unsteady flow in open channel flow and its application, Doctoral Thesis, Kyoto University, p.128, 1986. (in Japanese)

3. Inoue, K., Kawaike, K. and Hayashi, H.: Inundation flow modeling in urban area, Annual Journal of Hydraulic Engineering, JSCE, Vol.43, pp.533-538, 1999. (in Japanese)

4. 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)

5. Ito, T. (ed.) : Application and Basis of Numerical Simulation, Athens Publication, Tokyo, Japan, pp.206-207, 1971. (in Japanese)

6. Iwasa, Y. and Inoue, K. : Numerical effect of non-linear convective terms on two-dimensional flood flows invasion analysis, Hydrosoft '84, Hydraulic Engineering Software, Vol.2, pp.17-28, 1984.

7. Iwasa, Y. and Inoue, K. : 2-D and 3-D mathematical models for flood analysis, Proc.of the Japan-China(Taipei) Joint Seminar on Natural Hazard Mitigation, pp.475-484, 1989.

8. 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)

9. Watanabe, M., Etoh, T. and Murota, A. : A method of numerical analysis of sewage transient flow with lateral pipes, Journal of Hydraulic and Sanitary Engineering, JSCE, No.411/II-12, pp.81-90, 1989. (in Japanese)

APPENDIX – NOTATION

The following symbols are used in this paper:

a	=	waterhammer velocity;
A	=	cross – sectional area;
A_b	=	cross – sectional area at border;
A_p	=	plane area of node or block;
B	=	link width;
B_1	=	effective length of stairs;
B_0	=	pathway width;
B_s	=	assumed slot width;
D_c	=	height of ceiling;
DH	=	water level difference;
DX	=	distance between the center of the adjacent link and node or block;
g	=	gravitational acceleration;
h	=	water depth;
h_b	=	water depth at the border plane;
h_j	=	depth of block;
h_l	=	depth of link;
h_n	=	depth of node;
H	=	water stage from reference datum;
H_f	=	water level of inundation area;
H_o	=	crest level of bank;
H_r	=	water level of river;
L	=	length of bank break;
M, N	=	discharge flux in the (x, y) direction;
n	=	Manning coefficient;
q	=	lateral inflow discharge;
Q	=	discharge;
Q_0	=	overflow discharge;
R	=	hydraulic radius;
u, v	=	velocity in the (x, y) direction;
$\Delta x, \Delta y$	=	the respective grid size in the (x, y) direction;
Δx_l	=	mesh size of link;
μ	=	coefficient of perfect overflow;
μ'	=	coefficient of submerged overflow;
μ_0	=	discharge coefficient;
ρ_w	=	density of water; and
τ_{bx}, τ_{by}	=	bottom shear stress in the (x, y) direction.

(Received November 10, 1999 ; revised March 29, 2000)