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PREDICTION OF TRAFFIC DIFFICULTIES CAUSED BY INUNDATION DUE TO HEAVY RAINFALL IN KYOTO CITY

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SYNOPSIS

This study deals with traffic problems in the Kyoto urban area due to inundations caused by heavy rainfall. First, under normal conditions, a "time-of-day" user equilibrium traffic assignment is performed and traffic conditions on the network are computed. Next, assuming a heavy rainfall, an inundation flow analysis by means of unstructured meshes is made to obtain the water depth distribution. A similar traffic analysis is performed under inundation conditions, by changing the travel speed and traffic capacity based on the computed water depth of each link. Then, the degree of congestion and the travel time between major ODs are compared and discussed for normal conditions and when inundations occur. We found that the inundations at the southwest of the studied area including the underpass of JR line has an effect on the traffic network all over the city, and that traffic difficulties change with the beginning of rainfall, namely, the temporal change of inundation.

INTRODUCTION

Flood disasters occur often in urban areas around the world. Urban flooding may paralyze urban functions. If streets are submerged, traffic may be troubled or disrupted. It is very important to predict to what extent traffic difficulties occur due to urban flooding from a disaster preventive aspect. However, studies related to this field of research have been limited as far as we know.

Kagaya et al. (1) studied the traffic condition change due to inland water inundation in the north part of Sapporo City, Japan. In their analysis, links where inundation water depth was over 20cm were assumed to be completely disrupted and OD (origin-destination) data were assumed to be the same in both normal and inundation conditions. They noted that the network traffic capacity in the studied area changed because of inundation. They also discussed

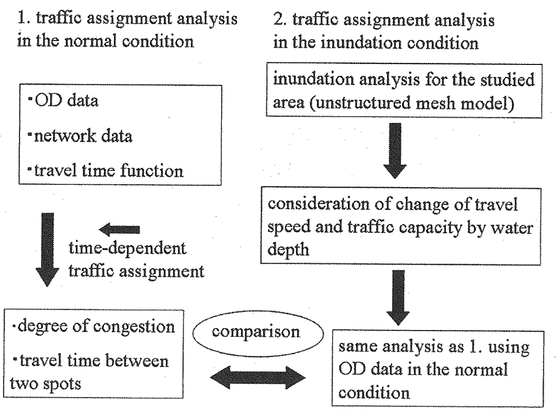

Fig.1 Framework of analysis

what measures could be taken against traffic difficulties.

Fukakusa et al. (2) combined traffic assignment analysis and inundation flow analysis in a more direct way for Kyoto city area. First, under the normal conditions, traffic assignment was performed and traffic distribution over network was computed. Next, assuming the overflow from the river, an inundation flow simulation was performed to obtain an inundation depth distribution. Then, a similar traffic analysis was performed under inundation conditions, by changing travel speed and traffic capacity based on the computed inundation depth of each link. Also, the degree of congestion and travel time between two spots were compared and discussed for the normal condition and the inundation one. However, in their analysis, the temporal changes of inundation and traffic assignment were not taken into account. Furthermore the inundation flow simulation was based on the pond model, and the underpass and detailed road conditions were not taken into consideration.

The basic scheme of this study is similar to the past study (2) but improves the above problems. In the traffic assignment analysis, a "time-of-day" user equilibrium traffic assignment is performed and a temporal traffic condition change on the network is computed. Next, assuming a heavy rainfall, an inundation flow analysis by the horizontally 2-D equations with unstructured meshes (Kawaike et al. (3)) was carried out to obtain the water depth distribution. In the inundation simulation model, urban flood characteristics, such as underground inundation and drainage due to sewer system were also taken into consideration. Thus, the inundation on the ground surface could be simulated in more detail.

The framework of analyses is shown in Fig. 1. The area which is examined is Kyoto City, the old capital of Japan. Toda (4) shows that the city is still vulnerable to flooding due to heavy rainfall.

INUNDATION SIMULATION

Inundation model

The surface inundation model is based on a horizontally two-dimensional unsteady flow model with unstructured meshes (3). The basic equations are continuity and momentum equations.

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=r-r_d \qquad (1)$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2 M\sqrt{u^2+v^2}}{h^{4/3}} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2 N\sqrt{u^2+v^2}}{h^{4/3}} \tag{3}$$

where h is the water depth, M and N are x and y directional discharge fluxes, respectively, r is effective rainfall intensity and r_d is the drainage ability by sewer system (drainage discharge per unit area). u and v are x and y directional velocity, respectively, H is water level from reference datum, g is gravity acceleration and n is the Manning's coefficient. In order to determine the effects of buildings, the occupying ratio (the ratio of the buildings area to the mesh area) and invasion ratio (the ratio of the side length, through which inundation water can go in or out, to the total side length) are introduced as is done by Inoue et al. (5).

Studied area and remarks on model treatment

The area examined is the central area of Kyoto City of about 80km^2 (Fig. 2). Kyoto City is surrounded by mountains to the north, the east, and the west. The Kamo River runs through the city center, the Katsura River on the west side and the Uji River on the south side. The area examined is surrounded by the left bank of the Katsura River and the right bank of the Uji River. The surface elevation distribution is shown in Fig. 3. In Kyoto City, slopes are fairly steep in north-south direction and the east side is higher than the west.

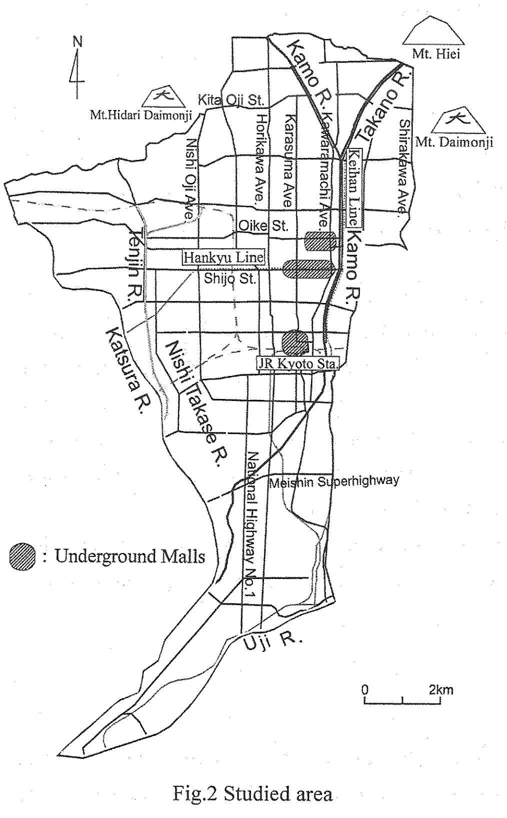

Fig.2 Studied area

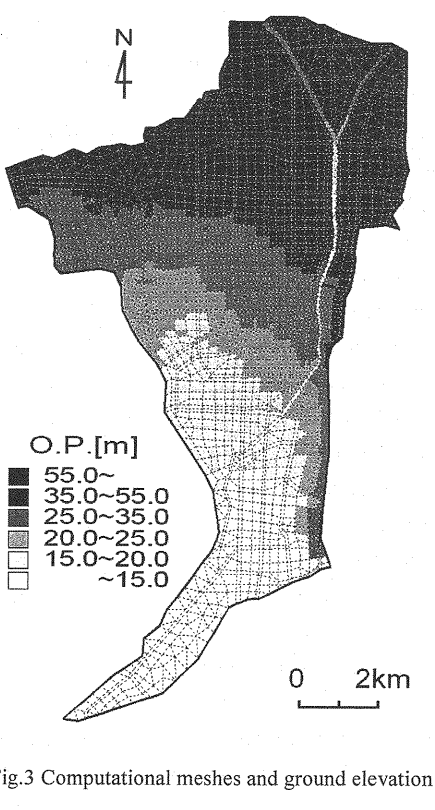

Fig.3 Computational meshes and ground elevation

The area which was investigated was divided into 2,504 computational meshes. The two larger rivers, the Kamo River and the Takano River were treated as open channels and expressed by means of meshes whose elevation is lower than the adjacent surface meshes. Here, we assumed the inundation due to heavy rainfall beyond the drainage ability, and did not assume the overflow from the rivers. The rivers were assumed to be dry initially, and we only considered the rainfall in the city area under investigation. At the downstream boundary, a step flow formula was utilized. The inflow from the city area into the rivers was expressed by an overflow or a step flow formula. In addition, the inflow to underground space such as underground mall and the subway was taken into consideration. A step of 15cm height of entrance was set up and the inflow was treated as a step flow.

As for the main sewer drainage system, the method adopted by Toda et al. (6) was utilized. We assumed a simple network comprising link and node, where a link is a sewer pipe and node is a drainage inlet like a manhole of sub-catchment. First, the total catchment area was divided into 26 sub-catchment areas. Each area is about 2-3 km^2. Next, the maximum drainage discharge for each sub-catchment area was allocated from the maximum drainage discharge of the pump station at the downstream end. Then, the drainage discharge, less than the allocated maximum discharge of each sub-catchment, was imposed at each node of the sewer network and flowed out from the downstream end pump station to rivers outside. If the allocated discharge was less than the drainage discharge Q_d, corresponding to the rainfall of 36.4mm/hr, 70% of the designed rainfall 52mm/hr, then it was replaced by Q_d. Kyoto City has not yet improved the rainwater drainage ability for the level of designed rainfall, and the net drainage ability has not been examined thoroughly. Therefore, through the preliminary studies, we assumed the drainage ability of 70% of the designed rainfall. Similarly, for the minor sewer drainage system, the lateral outflow of 36.4mm/hr was assumed to be uniform. Lastly the drainage ability of 100mm/hr was set at each underpass.

TRAFFIC ASSIGNMENT ANALYSIS

Time-of-day user equilibrium traffic assignment

We made a time-of-day user equilibrium traffic assignment analysis for the network in the studied area. The network which consists of major arterial roads is shown in Fig. 4. First, we assumed the realistic values of travel speed and traffic capacity of each link in the network. These values were determined by the results of a previous study (2).

Next, we applied the OD demand modification method to treat the residual traffic caused by congestion on road network. The residual traffic is defined herein as the traffic generated during a certain time slot but not reaching its destination within the time slot due to increase in travel time. In the OD demand modification method, the residual traffic is not loaded onto the road network during the focused time slot and the corresponding OD demand is forwarded and added to the OD demand in the subsequent time slot. The length of each time slot is assumed to be two hours in this study. By introducing the method, we were able to formulate the time-of-day traffic assignment as the network equilibrium model with elastic demand, and could apply Frank-Wolfe method to it.

We performed the time-of-day user equilibrium assignment and obtained the temporal change of link travel time and traffic congestion under normal conditions, namely no inundation condition. A degree of congestion is defined as the ratio of traffic volume to traffic capacity of each link.

Traffic assignment in inundation condition

Next, we obtained the inundation water depth of each road (each link of network) by means of the inundation analysis. In this investigation we assumed that only the link travel speed and traffic capacity change according to the

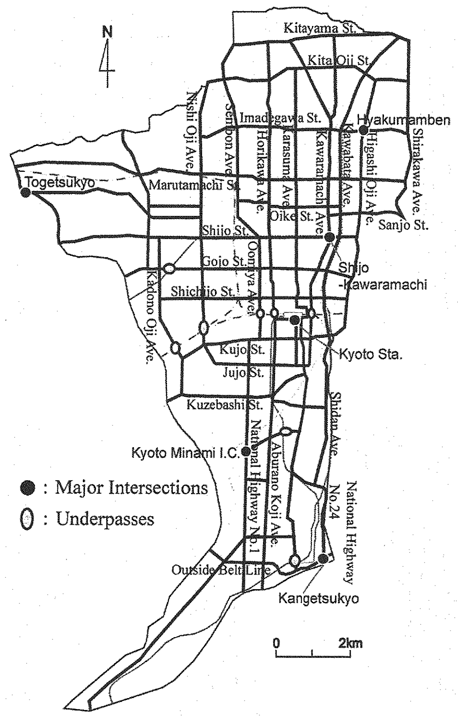

Fig.4 Studied network

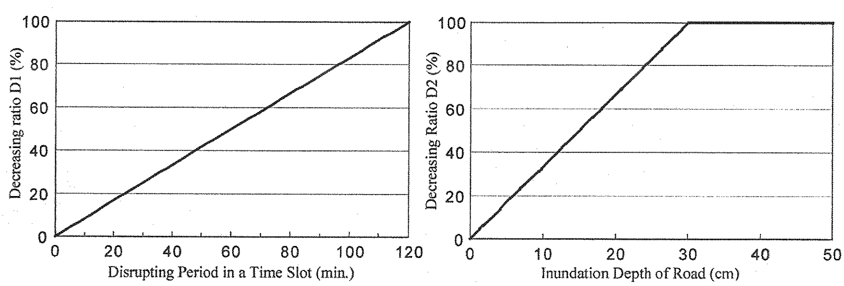

Fig.5 Decreasing ratios of travel speed and traffic capacity

inundation water depth and that OD demands are the same as in the normal condition.

We assumed that road was perfectly disrupted if the water depth is over 30cm, considering the wheel size of passenger vehicle and its engine trouble. We defined the values of decreasing ratios of travel speed and traffic volume, and used the disrupting period in a time slot and inundation depth as shown in Fig. 5, and obtained the following relation:

$$(1-D/100)=(1-D_1/100)\times(1-D_2/100) \tag{4}$$

where, D is the decreasing ratio in each time slot, D_1 is the decreasing ratio by disrupting period, and D_2 is the decreasing ratio by the averaged water depth during non-disrupting time. After determining the travel speed and the traffic capacity of each link at a time slot under inundation conditions, we conducted a traffic assignment analysis, and obtained the temporal change of degree of congestion of each link and travel time between two spots.

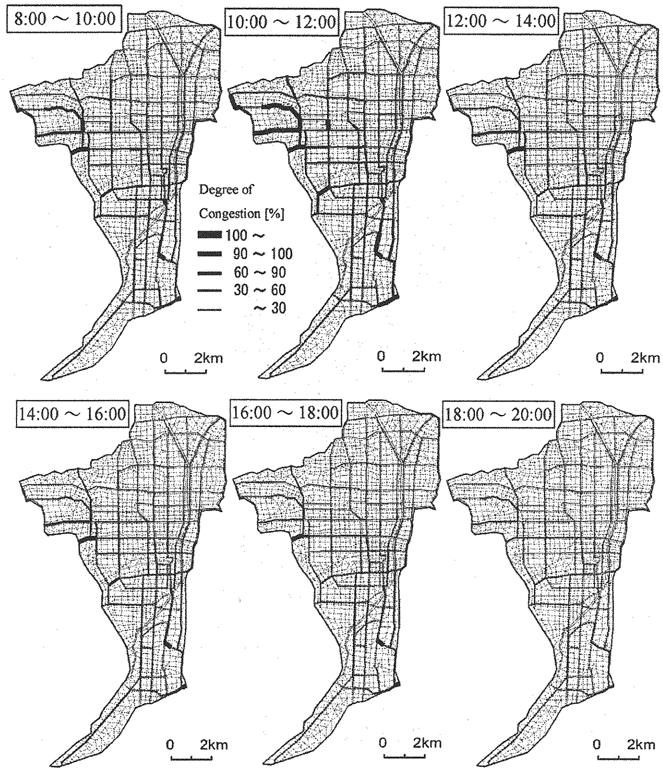

Fig.6 Degree of congestion in the normal condition

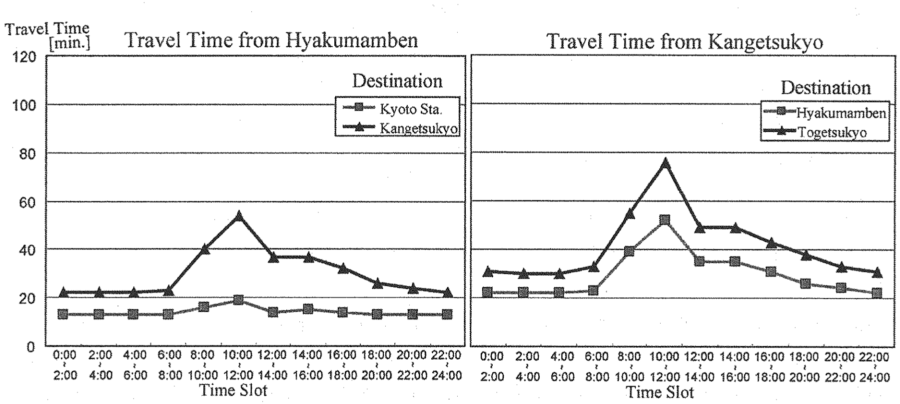

Fig.7 Travel time in the normal condition

RESULTS OF TRAFFIC DIFFICULTY ANALYSIS

Results in the Normal Condition

Fig. 6 shows the distribution of degree of congestion in the network which was investigated. Fig. 7 shows the travel time between two of the major intersections shown in Fig. 4. Under normal conditions, heavy congestion begins gradually around 8:00, and its peak appears between 10:00 and 12:00. It continues partially by 18:00. In the peak time, heavy congestion is distributed along National highway No. 24 and along the outside belt line in the south area, and along several streets in the western area. This result is almost in line with the real traffic condition of Kyoto City.

Traffic assignment in inundation condition

(1) Studied cases

Inundation analysis was conducted, assuming the heavy rainfall which caused Fukuoka flood in 1999 (Fig. 8). The rainfall was imposed uniformly over the area being examined, and the runoff ratio was set at 0.85. Fig. 9 shows the water depth distribution over 3 hours, 5 hours, and 7 hours after beginning of rainfall, respectively. The figure shows the inundation water flows to the southwest direction. There appears a high water depth in the area along the Nishi Takase River and the inundation can be observed in the south area near the Uji River. The results which were obtained were qualitatively similar with the past study (4). Also, the model used here is more elaborate than the pond model by Fukakusa et al. (2).

We executed four traffic assignment cases by changing the time of beginning of rainfall as shown in Table 1. After we study minutely Case 2 and Case 3, we compare the four cases each other. Fig. 10 and Fig. 11 show the degree of congestion of Case 2 and Case 3, respectively, and Fig. 12 shows a comparison of travel time in the inundation condition of the four cases.

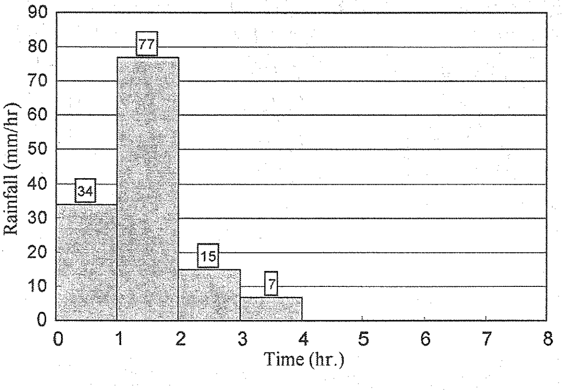

Fig.8 Rainfall condition of Fukuoka flood in 1999

Table 1 Traffic analysis cases

Case	Rainfall	Rainfall starting time
Case 1	Rainfall in Fukuoka flood in 1999 (runoff rate is set 0.85.)	0:00
Case 2		6:00
Case 3		12:00
Case 4		18:00

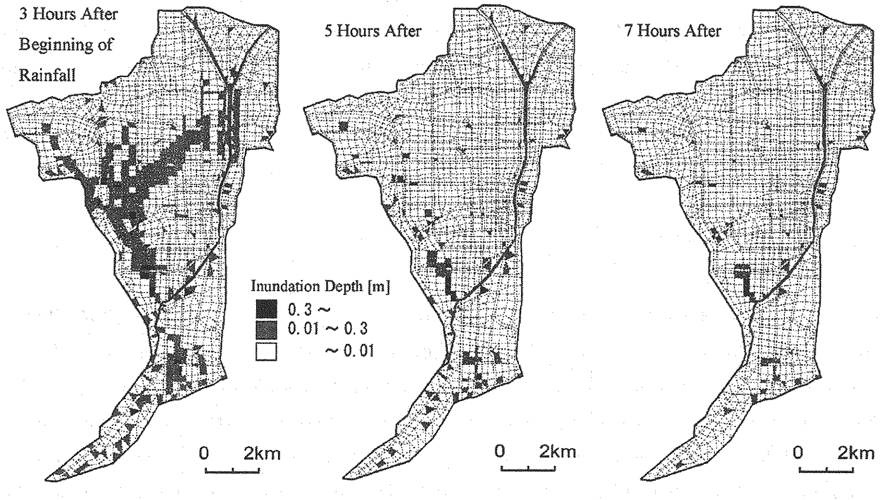

Fig.9 Computed inundation water depth distribution

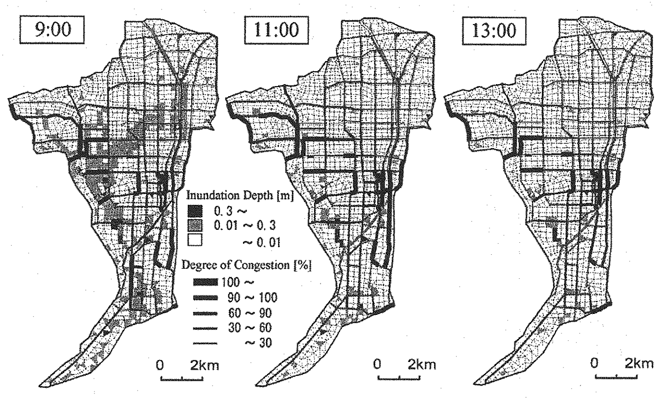

Fig.10 Degree of congestion in inundation (Case 2)

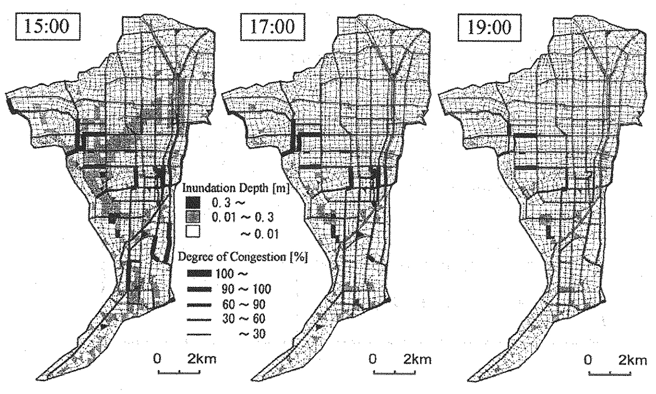

Fig.11 Degree of congestion in inundation (Case 3)

(2) Case 2 (rainfall starting time 6:00)

The inundation depth becomes high around 8:00 to 9:00, when the disrupting links occur in a wide area, especially, the arterial roads such as Horikawa Avenue, Nishi Oji Avenue and Kadono Oji Avenue are disrupted at the underpasses passing JR railway, and the consequent traffic congestion in the north-south direction occurs along Kawaramachi Avenue, Karasuma Avenue and Omiya Avenue. Even around 10:00 to 12:00, several disrupting links still exist, which increases the travel time. Due to the temporal disruption of Aburano Koji Avenue, many vehicles are made to bypass to National highway No.1 and No.24, which causes traffic problems in the south area.

(3) Case 3 (rainfall starting time 12:00)

In this case, it starts raining after the morning peak of traffic volume ends. Around 14:00 to 16:00, many links in the central area and the south area are congested. The travel time between 14:00 and 16:00 is longer than that between 10:00 and 12:00, and such congestion lasts long until night.

(4) Comparison among four cases

As for the degree of traffic problems, Case 2 shows the highest level, while Case 4 shows the lowest. In Case 2, severe traffic congestions are caused by heavy inundation in the morning, causing a decrease in traffic volume. Furthermore the disruption of link including underpass for a long duration is another reason for severe traffic problems in a wide studied area.

In Case 3, inundation occurs around noon after the peak of traffic volume, and disruption of several links continues for a long period of time from afternoon to night. While, in Case 2, inundation occurs in the morning, which overlaps the peak time of traffic volume, which causes the heavy road disruption from morning to noon. The degree of traffic congestion depends greatly on whether the inundation occurs before or after the time during 10:00 and 12:00 when the traffic volume shows its peak.

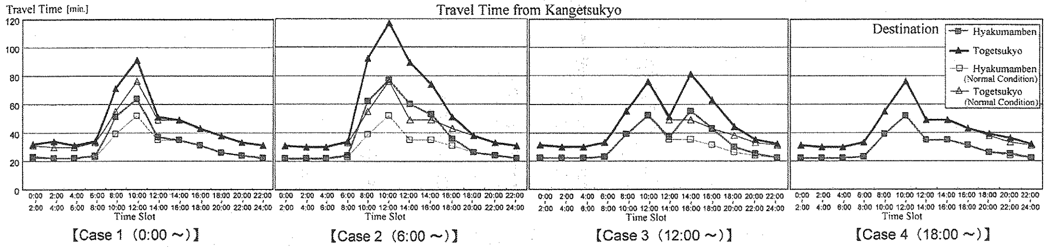

Fig.12 Travel time in the inundation condition

COUNTERMEASURES AT UNDERPASS

Search of underpass of bottleneck

The underpass passing JR railway most likely becomes a bottleneck of traffic in the north-south direction. In this study, we tried to find underpasses which greatly influence the traffic difficulties when inundation occurs. The underpasses which were examined are located at Kawaramachi Avenue, Horikawa Avenue, Nishi Oji Avenue and Kadono Oji Avenue (see Fig. 4). We conducted a traffic assignment simulation in which one of four underpasses was hypothetically removed under the same conditions as Case 2. The removal of the underpass was expressed by flattening the ground elevation and by decreasing the drainage ability of 100mm/hr to the standard sewer system one. We assumed that if the underpass had a significant influence on the traffic assignment, its removal would have a significant effect on the decrease in traffic problems. We changed the removed underpass one after another.

Fig. 13 and Fig. 14 show a comparison of the total link distance and the total travel time of congestion and disruption after underpass removal, respectively. These figures show that the underpasses at Kadono Oji Avenue and Horikawa Avenue give a larger influence than others, based on reductions in the total link distance and travel time of congestion between present condition and underpass removal cases.

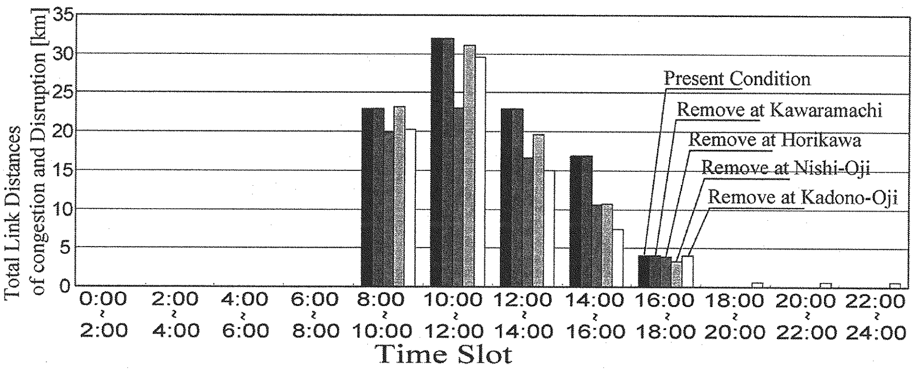

Fig.13 Comparison of total link distance of congestion and disruption in underpass removal

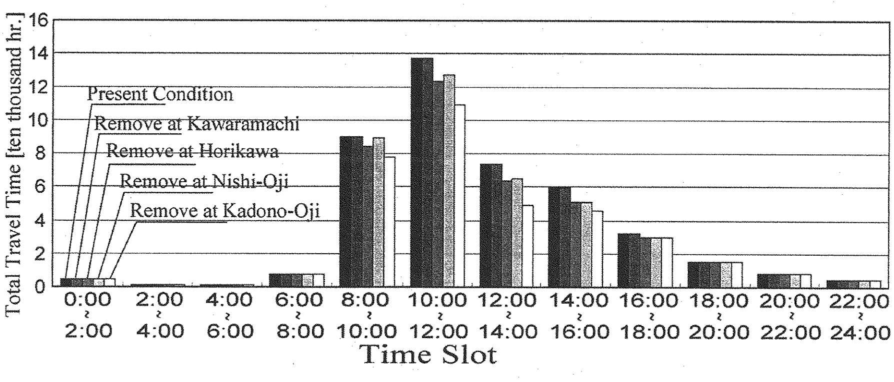

Fig.14 Comparison of total travel time of congestion and disruption in underpass removal

Increase of drainage ability increase

The underpasses passing JR railway are likely to be inundated, and they cause the traffic problems, especially in the north-south direction. At this stage, we take the two underpasses at Kadono Oji Avenue and Horikawa Avenue and consider the increase in rainfall drainage ability from 100mm/hr to 200mm/hr there. Fig. 15 and Fig. 16 show the degree of congestion and travel time as result of inundation, respectively, by underpass drainage ability increase under the same conditions as Case 2. When maximum inundation occurs, several links including Kadono Oji Avenue and Horikawa Avenue are still disrupted in spite of the drainage ability increase. After the peak of inundation, however, the drainage ability increase has a significant effect on the congestion reduction in the central area compared with Case 2. As for the travel time, though its peak value does not change during 10:00 and 12:00, it is greatly reduced as time passes, especially in the north-south direction.

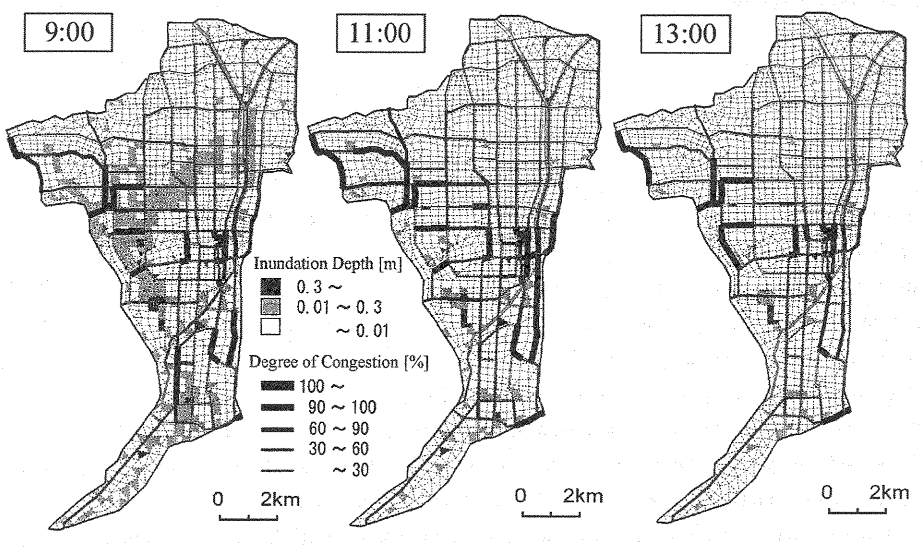

Fig.15 Degree of congestion in inundation by underpass drainage ability increase

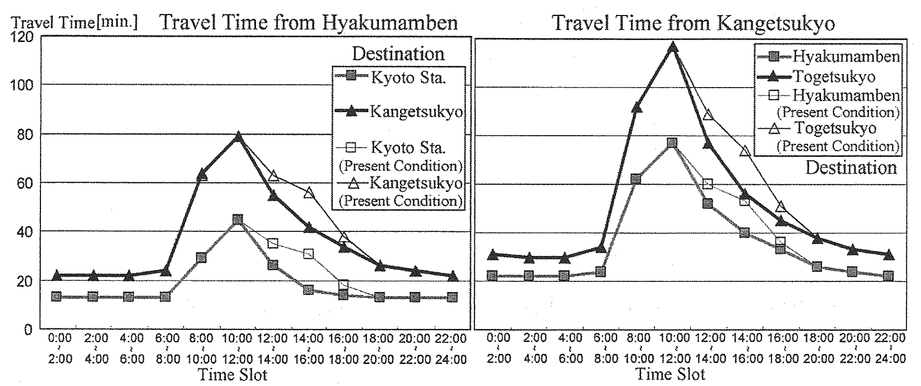

Fig.16 Travel time in inundation by underpass drainage ability increase

CONCLUDING REMARKS

The main results obtained through this study are as follows:

(1) A time-of-day user equilibrium traffic assignment analysis and an inundation flow analysis with unstructured meshes were combined. By means of this combined model, traffic problems caused by inundation due to heavy rainfall in Kyoto City could be expressed in more detail.

(2) Traffic problems change at the beginning time of rainfall, namely, the temporal change of inundation. When the rainfall occurs in the morning, the traffic problems are likely to become worse.

(3) If the underpass drainage ability increases, it has a significant effect on the improvement of traffic flow as time passes after the peak time of inundation.

REFERENCES

1. Kagaya,S., Uchida,K. and Hagiwara,T. : A Study on changes of network traffic capacity in the case of inundation in the northeast part of Sapporo City, Journal of Japan Society for Natural Disaster Science, Vol.21, No.4, pp. 401-415, 2003. (in Japanese)
2. Fukakusa,S., Toda,K. and Uno,N. : Study on Traffic difficulties caused by urban flood inundation, Advances in Hydro-Science and Engineering Volume VIII, Nagoya University, 2008.(CD-ROM)
3. Kawaike,K., Inoue,K., Toda,K. and Noguchi,M. : Inundation flow analysis due to heavy rainfall in low-lying river basin, Journal of Hydroscience and Hydraulic Engineering, JSCE, Vol.22, No.1, 1-14, 2004.
4. Toda,K. : Urban flooding and measures, Journal of Disaster Research, Vol.2, No.3, pp.143-152, 2007.
5. Inoue,K., Kawaike,K. and Hayashi,H. : Numerical simulation models on inundation flow in urban area, Journal of Hydroscience and Hydraulic Engineering, JSCE, Vol.18, No.1, pp.119-126, 2000.
6. Toda,K., Inoue,K. and Murase,S. : Numerical simulation of inundation flow due to heavy rainfall in urban area, Proc. '99 International Symposium on Flood Control, Beijing, China, pp.564-574, 1999.

APPENDIX – NOTATION

The following symbols are used in this paper:

D = decreasing ratio in each time slot;

D_1 = decreasing ratio by disrupting period;

D_2 = decreasing ratio by the averaged water depth during non-disrupting time;

g = gravity acceleration;

H = water level from reference datum;

h = water depth;

M, N = respective discharge flux per unit width in x and y directions;

n = Manning coefficient of roughness;

r = effective rainfall intensity;

r_d = drainage ability by sewer system (drainage discharge per unit area) ;

Q_d = drainage discharge corresponding to 70 % of the designed rainfall;

t = time;

u, v = respective flow velocity in x and y directions; and

x, y = coordinates of flow.

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