URBAN INUNDATION ANALYSIS CONSIDERING THE WATER BEHAVIOUR OF SUBWAY

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ABSTRACT

Recently, the risk and the countermeasures of water disaster has been examined for underground spaces in urban areas. In metropolitan areas subways and underground shopping malls are highly developed. If large scale inundation occurs there, flood damage becomes serious in the underground space. In Kyoto city and Fukuoka city, which are the target areas of this study, there are the risk of inundation due to the Kamo river flood and the Mikasa river flood, respectively. And Kyoto city and Fukuoka city have subway lines and underground shopping malls. Actually, the inundation disaster of the subway occurred at Fukuoka city in 1999 due to overflow from the Mikasa River. Moreover, in our study group, the urban inundation analysis model was developed in consideration of an analysis on the water behavior of underground spaces. In this study, the developed analysis model was applied to inundation situations in Kyoto city and Fukuoka city. From this study, analysis results show the feature of the inundation in Kyoto city and Fukuoka city. Moreover, flood water flowing into the underground spaces was reduce by the effect of the water stop board at the entrance of underground spaces. In addition, in the inundation analysis, analysis results using 10m grid are different from the analysis results using 50m grid, so in order to express the state of flooding in detail, the importance of detailed analysis is shown clearly.

Keywords: Inundation analysis model, Numerical simulation, Subway, Underground space

1. INTRODUCTION

Recently, the serious water disaster occurred due to heavy rain with wide areas and long periods under the influence of the global warming. As the occurrences of further natural disasters are concerned by progress of the global warming, the countermeasures for large scale inundation are very important.

In highly urbanized areas such as Tokyo, Osaka, and Nagoya in Japan, underground spaces are developed as under shopping mall and subway. It is easy to imagine that if a large scale inundation occurs in such an area, flood water will flow into the underground area and cause serious damage to people, economy and traffic. Actually, heavy rains caused the inundation of underground space at Hakata Station in Fukuoka city in June 1999 and July 2003. The water disaster that occurred in 1999 was caused by the flood of the Mikasa River and the Sanno Canal. In this water disaster, there were one dead person and serious damage of many urban facilities. In order to estimate such water disaster and examine the countermeasures, it is important to understand the inundation situation of the land and the underground space due to large scale inundation.

In recent years, studies on the inundation damage of underground space have been reported actively. Simulations of the inundation due to heavy rain and the evacuation have been examined in underground shopping malls located in Osaka, Tokyo, etc. by Ozaki et al. (2014), Sekine et al. (2003). Therefore, the inundation characteristics and the risk assessment, the realistic inundation countermeasures, and the evacuation countermeasures are discussed. In addition, Sekine et al. (2016) and Okabe et al. (2016) have been examined on inundation analysis in consideration of water behavior of subway.

The urban inundation analysis model has been developed in Tokyo, Osaka and Nagoya in consideration of the water behavior of the underground space by Murase et al. (2018). In this study, this analysis model is applied to the inundation situation of Fukuoka city and Kyoto city, where underground spaces are well developed. The aim of this study is to examine the feature of inundation situation, the effect of grid scale on inundation analysis, and evaluate the risk of underground space in the case of Fukuoka city and Kyoto city.

2. STUDY REGION

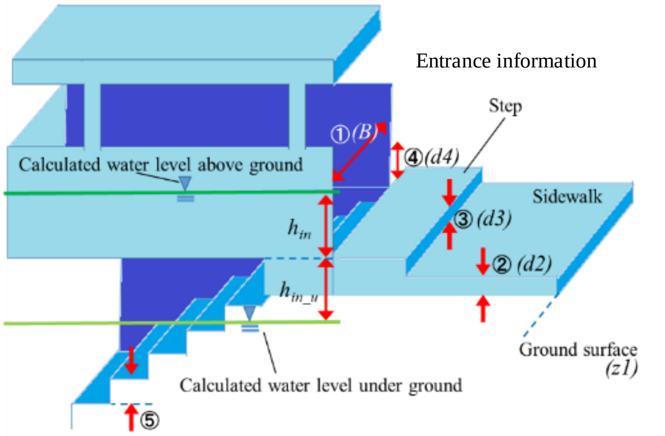
In this study, detailed informations of the subway entrance were required to develop the inundation analysis model considering the water behavior of underground spaces. Therefore, field survey was conducted in Fukuoka city and Kyoto city. Figure 1 shows the measured items.

2.1 Fukuoka city

The field survey was conducted in Fukuoka city on August 2, 2018. The entrance information was measured on three subway lines, the Hakozaki line, the Airport line, and the Nanakuma line. The number of the station and entrance are 35 and 184 respectively. As the ground elevation and the step height of the entrance of Hakata station is lower than the surround ground elevation, the topography around Hakata station has the feature which water gathers.

2.2 Kyoto city

The field survey was conducted in Kyoto city on July 26 and 27, 2019. The entrance information was measured on four subway lines, the Tozai line, the Hankyu line, the Keihan main line and Karasuma line. The number of the station and the entrance are 41 and 242 respectively. Moreover, At Kyoto station, there are 34 entrances to the underground space and the many entrances are located at north part of Kyoto station. As mention later, If a dike breaks in the Kamogawa river on the north side of Kyoto station, the floodwater flows to south and reach to Kyoto station. The water may inflow to the underground spaces of Kyoto station. Moreover, each station and an underground shopping mall are treated as one box on the analyis of water behaviour. As shown in Figure 2, Karasuma station and Kawaramachi station on Hankyu Kyoto line and Shijo station on Karasuma line are connected by underground passages. In this study, Karasuma station and Shijo station are considered as one station, and Kawaramachi station is treated as another one.



Survey items	
Check the location of entrance	Height of one step the stairs from basement to the station yard : ⑤
Entrance width (*B*) : ①	Number of steps from basement to station yard
Height from the ground surface to sidewalk (*d2*) : ②	Height of one step the stairs from the station yard to the platform
Height from the sidewalk to step (*d3*) : ③	Number of steps from the station yard to the platform
Water stop board height (*d4*) : ④	

Figure 1 Measurement items of field survey

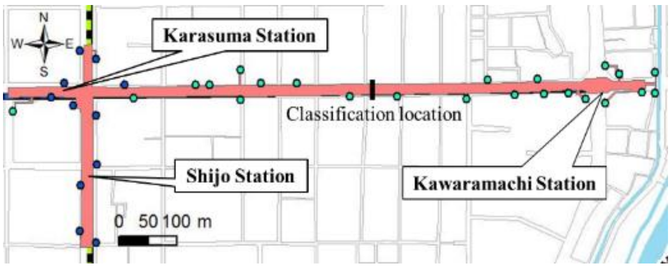


Figure 2 Model of Karasuma station, Shijo station and Kawaramachi station in Kyoto city

3. URBAN INUNDATION ANALYSIS MODEL

3.1 Inundation analysis model

A two dimensional continuity equation (1) and momentum equation (2), (3) were applied to inundation analysis on land.

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

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}=-gh\frac{\partial (z_G+h)}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)-\frac{\tau_{bx}}{\rho} \tag{2}$$

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}=-gh\frac{\partial (z_G+h)}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)-\frac{\tau_{bx}}{\rho} \tag{3}$$

where, x, y are coordinates , t is time, h is water depth, M, N are the flux (m^2/s) of the x, y coordinate respectively $(M = uh,\ N = vh)$, u, v are the water velocity of the x, y coordinate respectively, q_o is outflow discharge per unit area, $q_o = \sum q_n l_n / \Delta x \Delta y$ (q_n : cross inflow discharge per unit area (m/s), l_n : length of river section in grid (m), $\Delta x \Delta y$: area of grid (m^2)), g is the gravity acceleration, z_G is the ground elevation, $\varepsilon_x, \varepsilon_y$ are the eddy viscosity coefficient of the x, y coordinate respectively (the value of eddy viscosity coefficient is zero in this study), ρ is water density and τ_{bx}, τ_{by} are bottom share stress (Pa) of the x, y coordinate respectively. The bottom share stress is expressed by following equation (4), (5) using Manning's roughness coefficient.

$$\tau_{bx} = \rho g n^2 M \sqrt{u^2 + v^2} / h^{4/3} \tag{4}$$

$$\tau_{by} = \rho g n^2 N \sqrt{u^2 + v^2} / h^{4/3} \tag{5}$$

where, n is Manning's roughness coefficient.

3.2 Analysis model on the water behavior of underground shopping mall and subway station

The continuity equation of the underground shopping mall and subway station is shown following equation (6).

$$A_u \frac{\partial h_u}{\partial t} = \sum Q_e - \sum Q_o \tag{6}$$

where, A_u is horizontal area of the underground shopping mall and subway stations, h_u is the water depth, Q_e is the inflow discharge into the underground shopping mall and subway station, Q_o is inflow discharge into the subway line. The ground elevation near the entrance of the underground space was determined from 5m mesh ground elevation value, and it was used as the elevation data of the road ($z1$). Using this value, the measured entrance information (height from the ground surface to sidewalk ($d2$), height from the sidewalk to step ($d3$), water stop board height ($d4$), entrance width (B)), and the water elevation(H) obtained by the numerical analysis, the water depth at the entrance (h_{in}) is obtained by equation (7). However, if h_{in} is greater than the calculated water depth, h_{in} is replaced with the water depth calculated by analysis. The water depth of the underground shopping malls and subway station at the step of entrance (h_{in_u}) is calculated by equation(8). In the h_{in} and h_{in_u}, the large value is h_1, the other is h_2. The inflow discharge Q_e is calculated by using of equation (9).

$$h_{in} = H - (z1 + d2 + d3 + d4) \tag{7}$$

$$h_{in\_u} = h_u + z_{bu} - (z1 + d2 + d3) \tag{8}$$

$$\begin{aligned} h_2/h_1 &\leqq 2/3 \qquad & Q_e &= \mu B h_1 \sqrt{2gh_1} \\ h_2/h_1 &> 2/3 \qquad & Q_e &= \mu' B h_2 \sqrt{2g(h_1 - h_2)} \end{aligned} \tag{9}$$

where, h_u is water depth of underground shopping malls and subway station, z_{bu} is bottom elevation of underground shopping malls and subway station, μ is 0.35, μ' is 0.91. Also, the water depth of subway line from bottom elevation of underground shopping mall and subway station (h_{s_u}) is calculated by following equation (10). In the h_{in_u} and h_{s_u}, the large value is h_1, the other is h_2. The inflow discharge Q_o is calculated by using of equation (11).

$$h_{s\_u} = h_s + z_{bs} - z_{bu} \tag{10}$$

$$\begin{aligned} h_2/h_1 &\leqq 2/3 \qquad & Q_o &= \mu L h_1 \sqrt{2gh_1} \\ h_2/h_1 &> 2/3 \qquad & Q_o &= \mu' L h_2 \sqrt{2g(h_1 - h_2)} \end{aligned} \tag{11}$$

where, h_s is water depth of subway line, z_{bs} is bottom elevation of subway line, L is the circumferential length of the entrance of the subway line, μ is 0.35, μ' is 0.91.

3.3 Analysis model on the water behavior of subway line

The water behavior of the subway line is analysis by one dimensional unsteady flow model with slot model. Following equations (12), (13) are used for analysis.

$$\frac{\partial A_s}{\partial t} + \frac{\partial Q_s}{\partial x} = q_o \tag{12}$$

$$\frac{\partial Q_s}{\partial t} + \frac{\partial U_s Q_s}{\partial x} = -g A_s \frac{\partial (h_s + z_{bs})}{\partial x} - \frac{g n_s^2 Q_s |U_s|}{R_s^{4/3}} \tag{13}$$

where, A_s is the cross sectional related the water flow of the subway line, Q_s is the discharge, q_o is the lateral discharge per unit length ($q_o = Q_o/\Delta x_s$), $h_s$is the water depth of subway line, U_s is the velocity, n_s is the roughness coefficient of Manning, R_s is the hydraulic radius. Slot width is calculated by gA_{SS}/C^2, A_{SS} is cross section of subway line, C is the wave velocity (assumed 20m/s). The cross section of subway line is assumed that the width is 7.75m and height is 4.35m. The transport of flood water is considered at the transfer station in this study. At the transfer station, the discharge is calculated by equation (11) on all related subway lines. Therefore, the connection of the subway line and the related transport of flood water are considered at the transfer station.

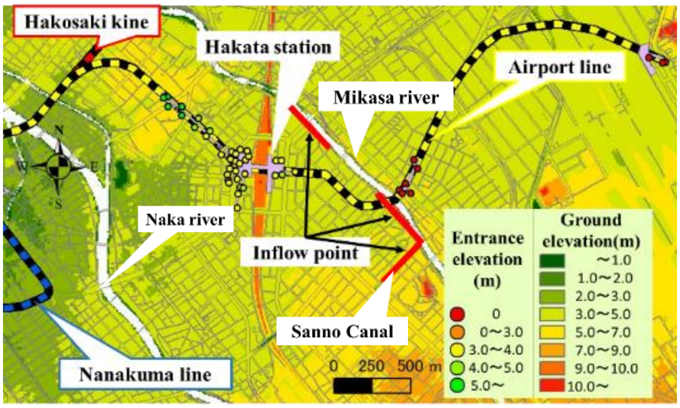


Figure 3 Analysis area of Fukuoka city

4. ANALYSIS AREA AND CONDITIONS

The ground elevation information was set as 10m and 50m. The area value of underground shopping mall and subway station was obtained from information on the web (ex. yahoo map). In addition, the horizontal shape of the subway line was determined using by the web information and GIS, and the elevation of subway line between two station was assumed to change linearly based on the elevation of subway line at each station platform in underground. Moreover, It was assumed that the bottom elevation of underground shopping mall and subway station is 0.5m above the cross ceiling of the section of the subway line. At the transfer station, multiple elevation of bottom appears, so the highest value was the elevation of underground shopping mall and subway station, and it was assumed that the subway line is connected the station by the entrance with circumference of 20m. Does not consider features on the ground.

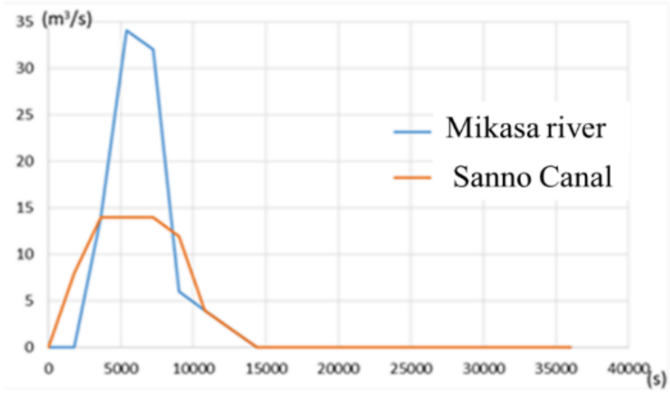


Figure 4 Discharge hydrograph

4.1 Fukuoka city

The inflow of the Mikasa river and the Sanno Canal are considered in this study, because the inundation (from inflow point) of Fukuoka city in 1999 is study topics. Figure 3 shows the analysis area of Fukuoka city (grid size is 10m). In the area near Hakata Station, the underpass is modified with the elevation of the surrounded road. The Figure 4 shows the inflow discharge of the boundary condition. The analysis time is 10 hours.

4.2 Kyoto city

The inundation water behavior due to the flood of the Kamo River is treated in this study. Figure 5 shows the analysis area of Kyoto city (grid size is 10m). A constant overflow discharge (50m^3/s) is set at the inflow point with 180 minutes. The inflow point which is shown in Figure 5 is between Sanjyo bridge and Oike bridge. In

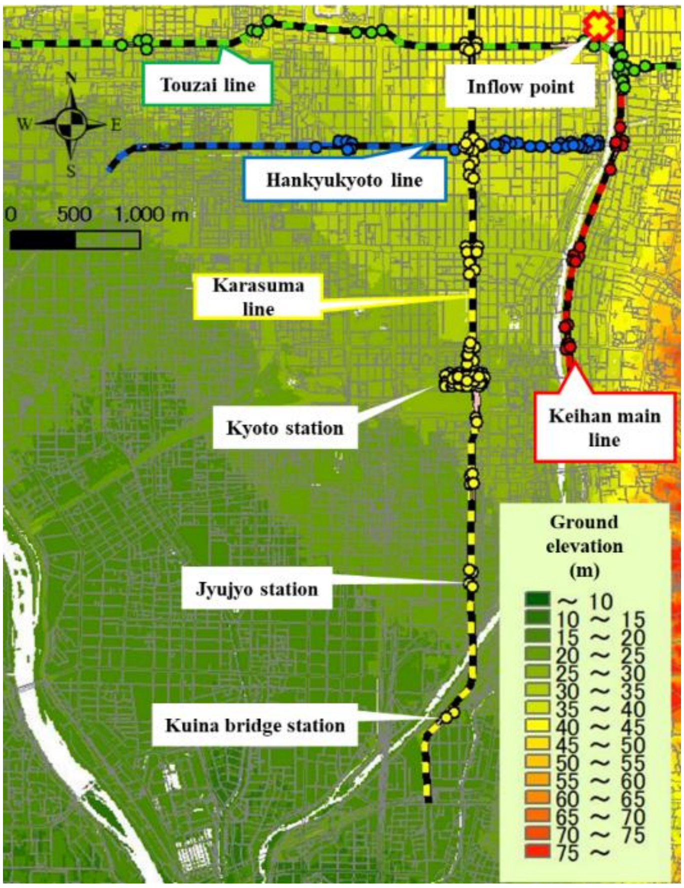


Figure 5 Analysis area of Kyoto city

addition, the detailed ground elevation information can be expressed by 10m grid. The analysis time is 10 hours.

5. ANALYSIS RESULTS

5.1 Fukuoka city

5.1.1 Feature of the inundation situation and the Effect of grid size on inundation analysis

Figure 6 shows the maximum water depth and the water depth of the subway line at the end of the analysis time with the 10m grid and 50m grid, respectively. In this inundation situation, the flood water flows from east part to west part around Hakata station. Although there was not much difference by the comparison of these results, the inundation area of 10m grid extends to the south part near the Naka River. Moreover, the range with the inundation depth of 0.2m to 4.0m becomes large on the inundation of the subway line in the case of 10m grid. The inflow water volume of the underground space was 20300m^3 for 10m grid and 12300 m^3 for 50m grid. Therefore, although there is no quantitative comparison with past disasters, there is a large difference on the amount of water of the underground spaces in analysis results with fine grid and corse grid, the fine analysis grid and the related ground elevation information should be use for the detailed analysis.

5.1.2 Transport characteristics of flood water and the risk assessment of underground space

Figure 7 shows the temporal change of analysis results. In the analysis results of two hours after the start of the analysis, the flood water reached at Hakata station, and the flood water start to flow into the underground space. Furthermore, in the results of three hours after the start of analysis, the flood water greatly spread to the west, and in the results of four hours after the start of the analysis, the inundation spread to the eastern subway line. It is considered that such water behavior of the subway line is caused by the elevation of the subway line. As shown in Figure 8, the gradient of the subway line in the west side of Hakata station has a steeper slope than the east side, and the flood water of the subway line spreads away immediately. However, the flood water of the subway line in the east side of Hakata station is gentle slope, so the spreading speed is slow. Thus, the underground space is dangerous because the flood water of the underground space spreads faster than the flood water of the ground.

5.2 Kyoto city

5.2.1 Risk assessment of underground space and change of inundation area by refinement of ground conditions

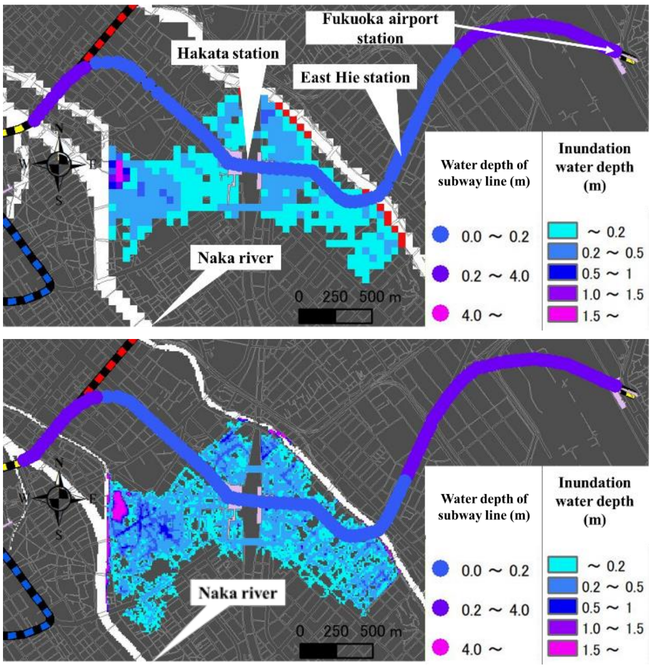


Figure 6 Maximum water depth (upper:50m lower:10m)

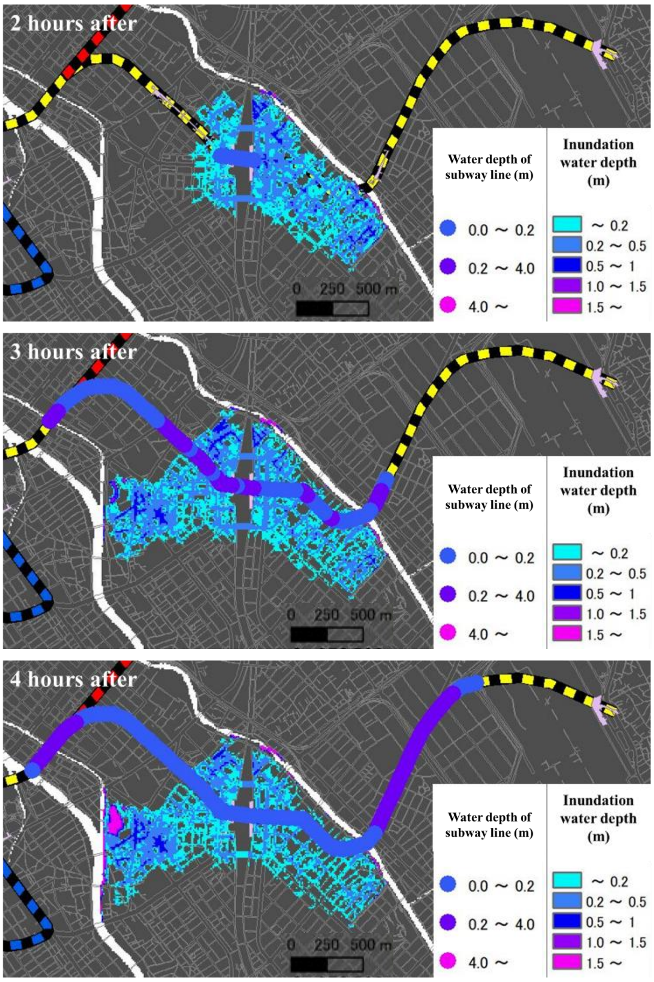


Figure 7 Temporal change of analysis result(Fukuoka city)

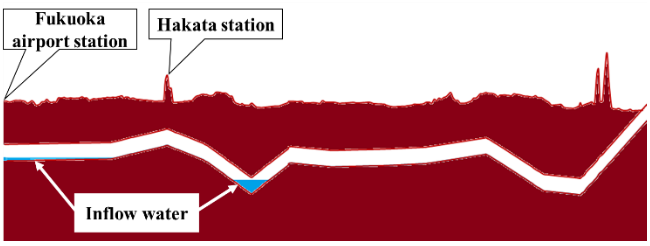


Figure 8 Sectional view of Airport line

Figure 9 shows the distribution of the maximum water depth on the 10m grid and the water depth of the subway line at the end of the analysis time. The large difference of the ground elevation between north part and south part is feature of the topography of the Kyoto city. It was found that the flood water flows to south part along the Kamo river from inflow point by the Figure 9, and the inundation area spread southwest near Kyoto station. From such as inundation area, the inflow of flood water to the Tozai line was small, and large scale inundation of the subway line was observed on Hankyu Kyoto line and Karasuma line. The inflow discharge to Kyoto station is the largest on Karasuma line, and the subway line near Kuina bridge station was submerged by water depth of 4m or more. It was indicates that the subway is full.

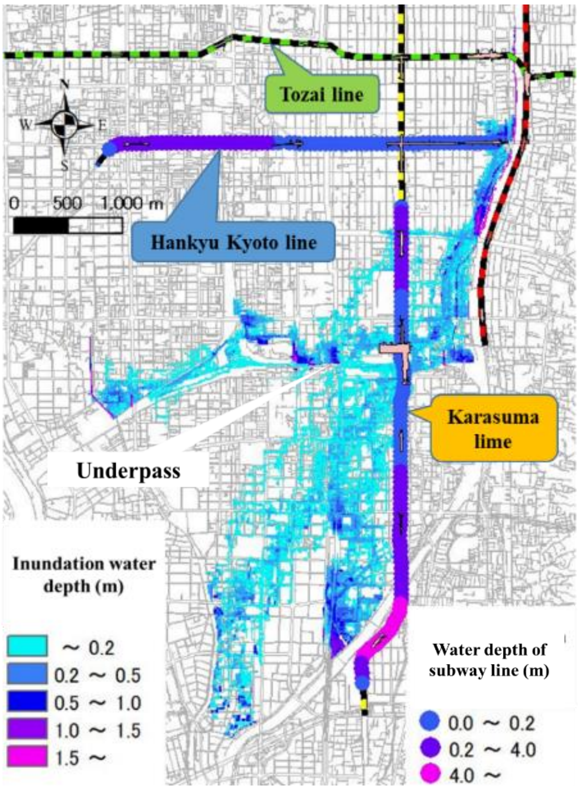


Figure 9 Maximum water depth on the land and water depth of subway line

The effect of the underpass near Kyoto station was not considered in the analysis results in Figure 9. The maximum inundation water depth is shown in the Figure 10 under consideration of the underpass near Kyoto station. There was no significantly difference in the state of inundation near Kyoto station, but the inundation area on the west side from Kyoto station was significantly reduced by considering the underpass. It was found that flood water spread to the south through the underpass because the ground was lowered by considering the underpass. The underpass is influenced facility on the water behavior of urban inundation. It is important to consider the effect of the facilities related the water behavior of the urban inundation in the analysis method.

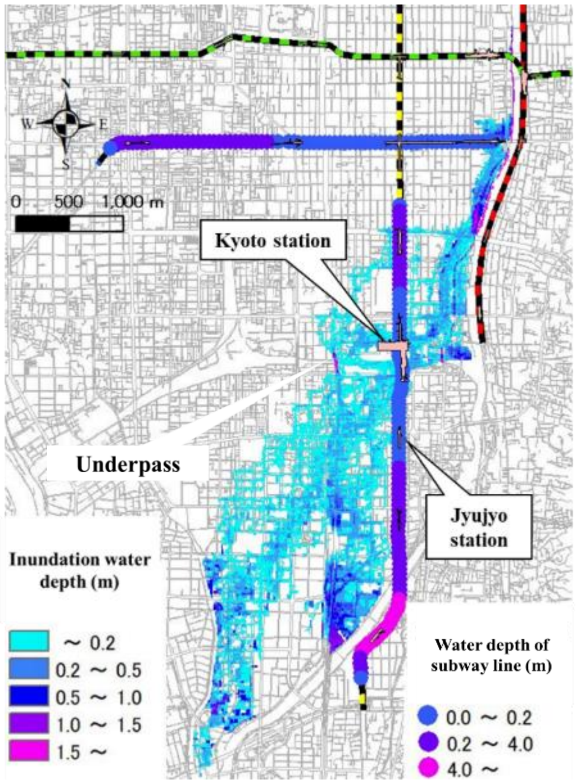


Figure 10 Maximum water depth on the land and water depth of subway line (consideration of underpass)

Figure 11 shows the temporal change of the distribution of the water depth on the land and the subway line. On the analysis results of 2 hours after the inflow, almost all section of Hankyu Kyoto line exceeded the inundation depth of 0.2m, and the flood water flowed at Kyoto station on the Karasuma line. As the spread of flood water of the subway was faster than ground, it is necessary to take the countermeasures. Moreover, the large inundation in the underground space occurred at Kuina bridge station where located on the opposite side of Kamo river. It is necessary to consider the countermeasure at the location of large inundation in the subway line.

5.2.2 Effectiveness of water stop board

Figure 12 shows the distribution of maximum inundation water depth on the land and water depth of the subway in consideration of water stop board. In this study, the water stop board is set at the entrance of underground spaces. On the inundation of underground spaces, the inundation did not occur at Hankyu Kyoto line due to the setting of the water stop board. On the other hand, the inflow of flood water occurred at Karasuma line, but the inundation situation become small more than the analysis results without water stop board. The inflow water volume of the underground space was 73300m^3 without the water stop board and 4890m^3 with the water stop board. From these analysis results, the effect of the water stop board is shown.

6. CONCLUSIONS

In this study, the urban inundation analysis model was developed considering the water behavior of the

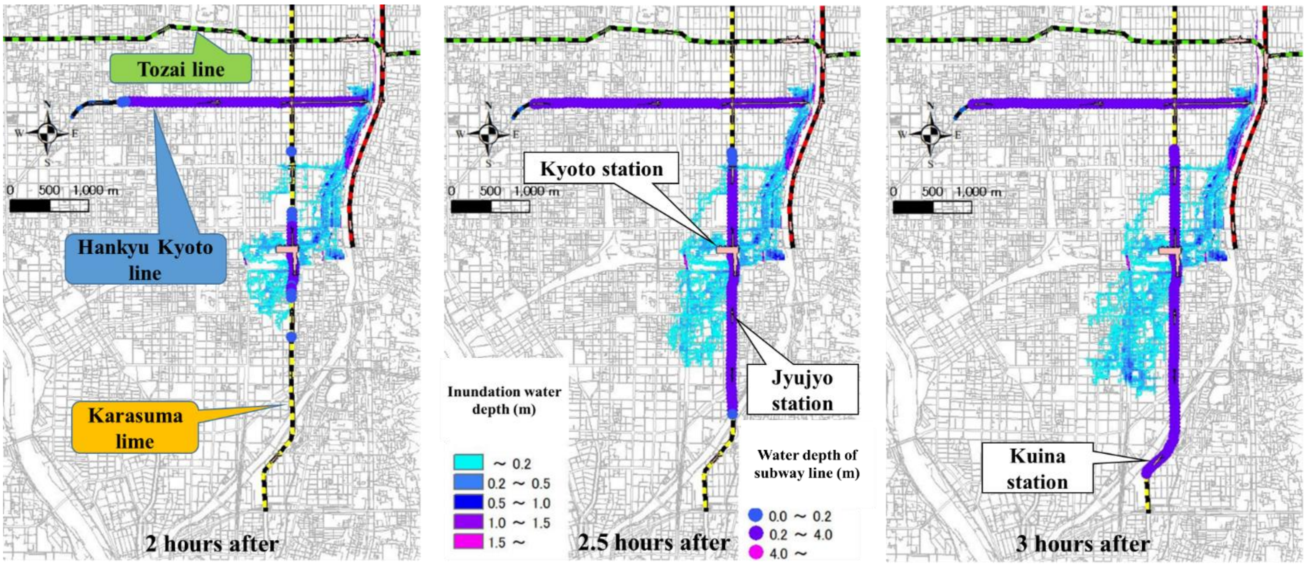


Figure 11 Temporal change of the inundation situation on the land and subway line(Kyoto city)

underground space and the proposed analysis model was applied to the inundation of Fukuoka city and Kyoto city. The obtained results are shown below.

1) The features of the inundation situation are shown in the analysis case of Fukuoka city and Kyoto city. Especially, because the inundation of the subway is indicated on the reproduction calculation of Fukuoka flood damage in 1991, the validity of the analysis model was indicated. In addition, when compared with similar research results by Toda et al.(2005), There were slight differences, but the results were generally the same.

2) It was found that the flood water that flowed into the underground space propagated through the subway line. In addition, it was found that the underground space is dangerous in flood because the propagation speed of the subway line is faster than inundation on the land and the submerged area occurs.

3) The difference of analysis results was obtained using small and rough analysis grid in Fukuoka city. Therefore, the fine analysis grid and the related ground elevation should be use for the detailed analysis.

4) The effect of the water stop board is shown from the analysis results (inflow of flood water into the underground) with and without water stop board at entrance of the underground space. Moreover, it is important to consider the effect of the facilities related the water behavior of the urban inundation in the analysis method. It is necessary to study it in the future.

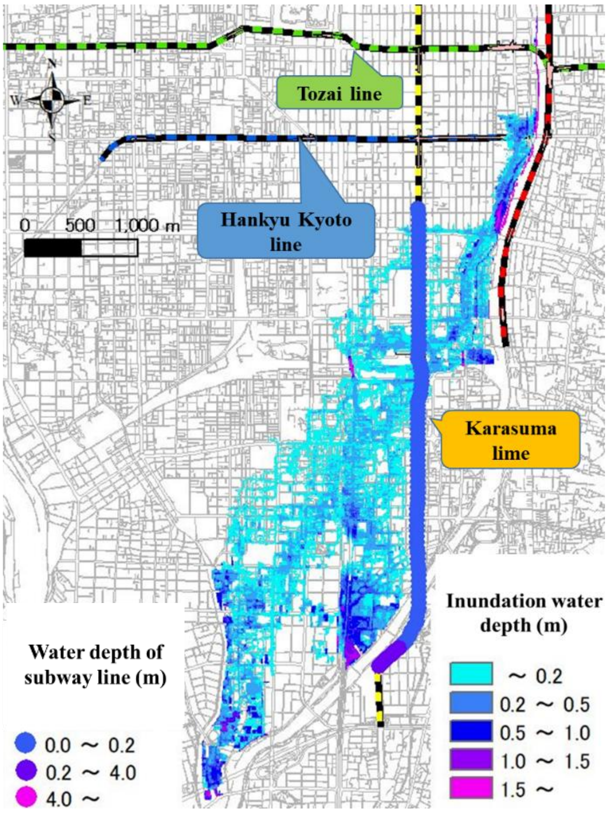


Figure 12 Maximum water depth on the land and water depth of subway line (consideration of water stop board)

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