# UNDERGROUND INUNDATION BY PLUVIAL FLOOD IN FULLY URBANIZED AREA OF OSAKA

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## ABSTRACT

In recent years, the frequency of local short-time heavy rain in urban areas is increasing. On August 27, 2013, an extreme heavy rain of 77.5mm per hour was observed in Osaka city. At this time, inundation caused damage such as flooding above floor level. In addition, flood water flowed into the mega-underground space in Osaka city, but there was no casualty. When local heavy rain would fall in a short time, not only pluvial flooding but also the risk of underground inundation was increasing. In this study, a simulation model considering sewerage drainage system in Tsumori treatment area in Osaka city is built. Underground inundation is investigated in the case of extreme rainfall condition of which maximum rainfall intensity was 146.5mm/hr in 2008 Okazaki flood. The results show that about 80% of the roads are flooded, and there were places where the flood depth is 1m or more. The inflow into the underground space goes through the subway station entrance. In particular, Osaka Metro Awaza Station has a high risk of inflow. Beside, in the underground malls, the inflow of flood water is smaller than the subway and underground parking lot. At underpasses, the inflow start time is fastest in underground spaces. In addition, the water depth exceeds the escape limit water depth of 0.56m in about 50 minutes from the beginning of rainfall. The inflow characteristics through the underground entrances in the Tsumori treatment area are clarified.

*Keywords*: pluvial flood, short-time rainfall, underground inundation, drainage area

## 1. INTRODUCTION

Frequency of local short-time heavy rain in urban areas is increasing recently. According to the Japan Meteorological Agency, rainfalls of 50 mm/hr or more have increased about 1.4 times in 10 years from 2008 to 2017 compared to those in 1976. Also, rainfalls of 80 mm/hr or more have increased about 1.6 times. In urban areas, rainwater drainage depends on sewerage due to the increase in impervious areas. In addition, using underground spaces such as underground malls and subways are progressing to make effective use of space. When local heavy rainfall happens in a short time, not only pluvial flooding but also the risk of underground inundation increases. Morikane et al. have considered the danger of underground space by pluvial flood. According to the result of previous study, flood condition on the ground has affected the inundation process of the underground space. Terada et al. has investigated how the intruding water spreads across the subway network due to pluvial flood. From the result, flooded water has broadly spread across in the subway network. In previous studies, inundation simulation by pluvial flood hasn't been done for other areas except the Ebie treatment area in Osaka City. In this study, a simulation model of InfoWorks ICM considering sewerage drainage system in the Tsumori treatment area which connect to the Ebie treatment area by subway tracks is built. Also, the inflow characteristics through the underground entrances in the Tsumori treatment area are discussed.

## 2. STUDY AREA AND METHOD

### 2.1 Study area

Study area is Tsumori treatment area in the central Osaka. Figure 1 shows the drainage system, sewage treatment plant and power water stations in the study area. This area has 5 pumping stations and treatment plants, and the catchment area is 19.62km$^2$. Rainwater is drained only by the drainage system of which design rainfall intensity is 60mm/hr. Ground level becomes lower from east "Uemachi Plateau" to west "Kizugawa River". Figure 2 shows the position of the mega-underground spaces in the study area. The underground entrances are 261 in the subway (31 stations), 71 in the underground mall (3 places), and 27 in the underground parking lot (10 places). There are also 5 underpasses.

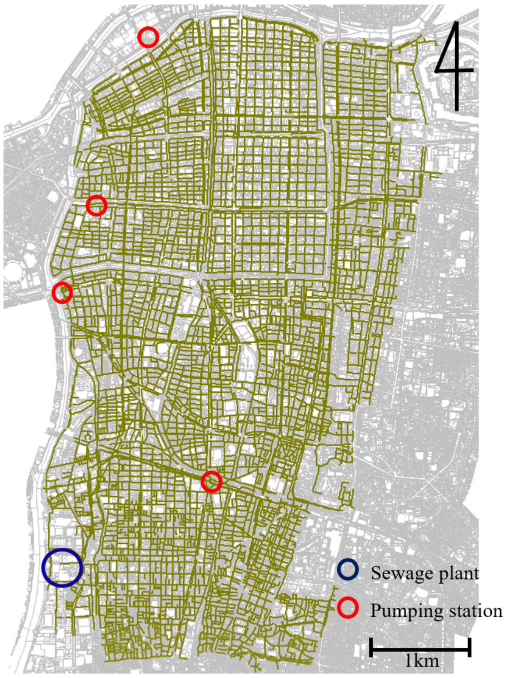


Figure 1. Study area
(drainage system and pump st.)

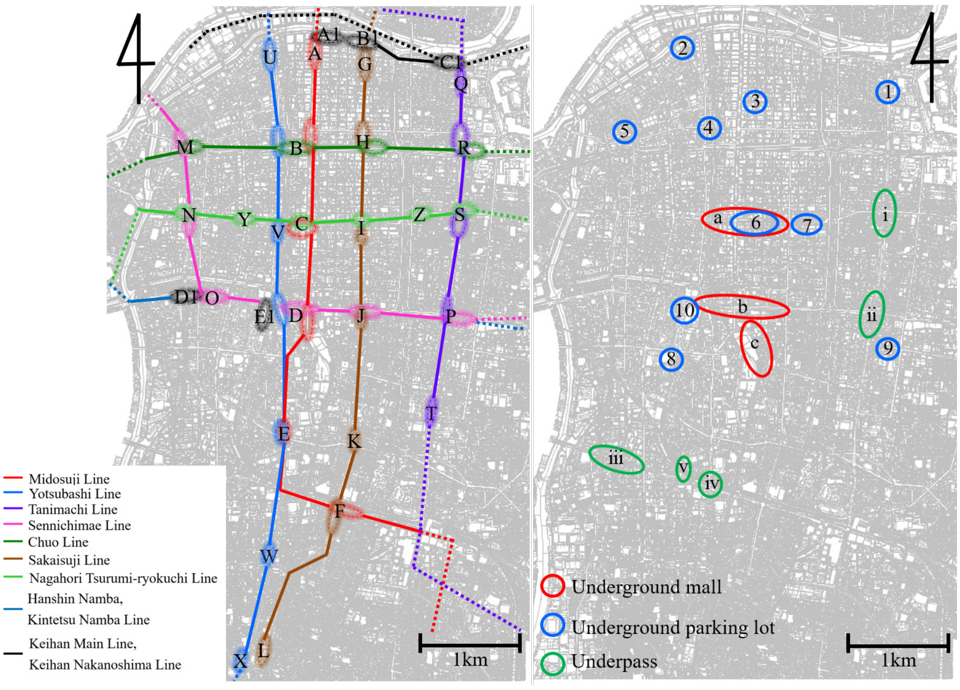


Figure 2. mega-underground space
(left: subway network, right: other space)

## 2.2 Inundation simulation model

The ground level flooding and the inflow through the underground entrances are calculated by InfoWorks ICM. Figure 3 shows overview of Infworks model. This model is using 1D-2D urban drainage model. Surface model calculates the amount of effective rainfall that flow into sewerage drainage pipes. Flow in drainage pipes is treated by using 1D Preissman Slot model considering pipes larger than 0.15 m in diameter (Sewerage pipeline model). The ground level flooding is calculated by using a 2D shallow flow model with unstructured mesh (Ground flood model). Floodwater flows only on roads and do not flows into residential areas such as buildings. Entrance model is treated as rectangular weirs and inflow discharge is calculated in Eq. (1). The width and step-up height of all entrances are modeled on the basis of our field surveys. Floodwater passing through the entrance model ignores by draining from the outfall.

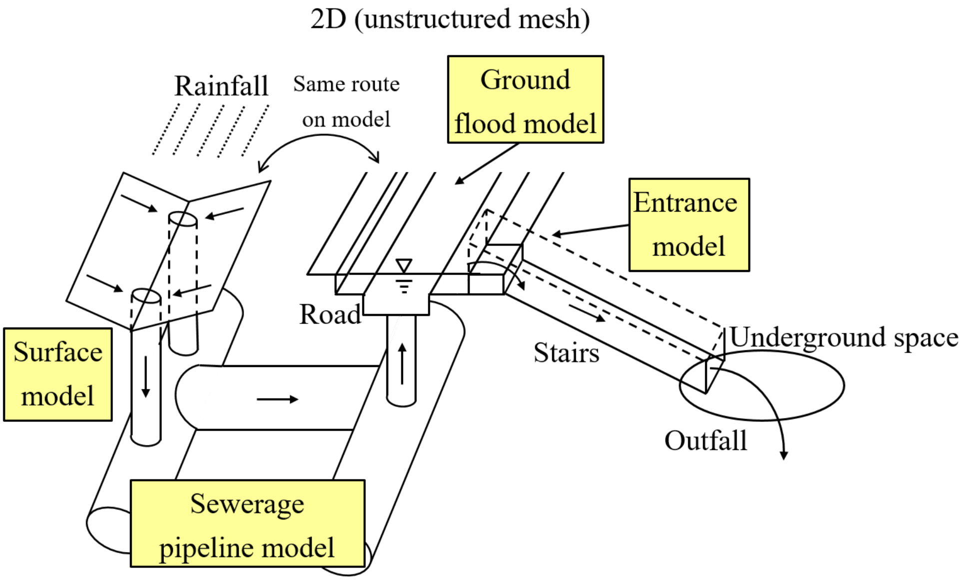


Figure 3. Infoworks model

$$Q = C_d\sqrt{g}Bh^{3/2} \tag{1}$$

where $Q$ is inflow discharge, $C_d$ is discharge coefficient (0.85), $g$ is gravity acceleration, $B$ is width of entrance, $h$ is overflow depth.

## 2.3 Rainfall condition

In this study, underground inundation is investigating in the case of extreme rainfall condition of which maximum rainfall intensity is 146.5mm/hr in 2008 Okazaki flood. Figure 4 shows the rainfall. The total rainfall is 242.0mm, and the rainfall exceeding 60mm/hr which is the sewer drainage capacity of Osaka City is 98.5mm.

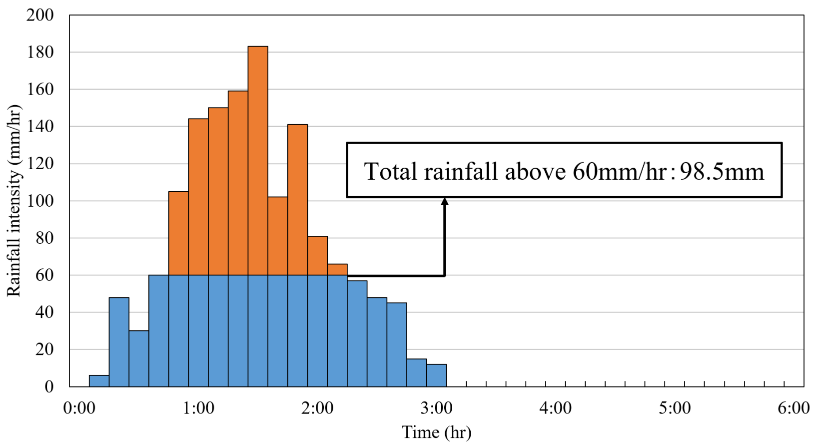


Figure 4. Subject rainfall hyetograph

## 3. GROUND LEVEL INUNDATION

Figure 5 shows the process of pluvial flooding and the maximum depth of inundation. The maximum inundation area only on the road was about 443ha (Total road area is about 553 ha). About 80% of the roads were flooded. The entire area was flooded at 2 hours from the start of rainfall. The inundation depth was more than 1 m in the northern, northwestern, western, central southern and southwestern areas. 3 hours after, the ground inundation showed a peak. This peak time is about 1.5 hours different from rainfall peak.

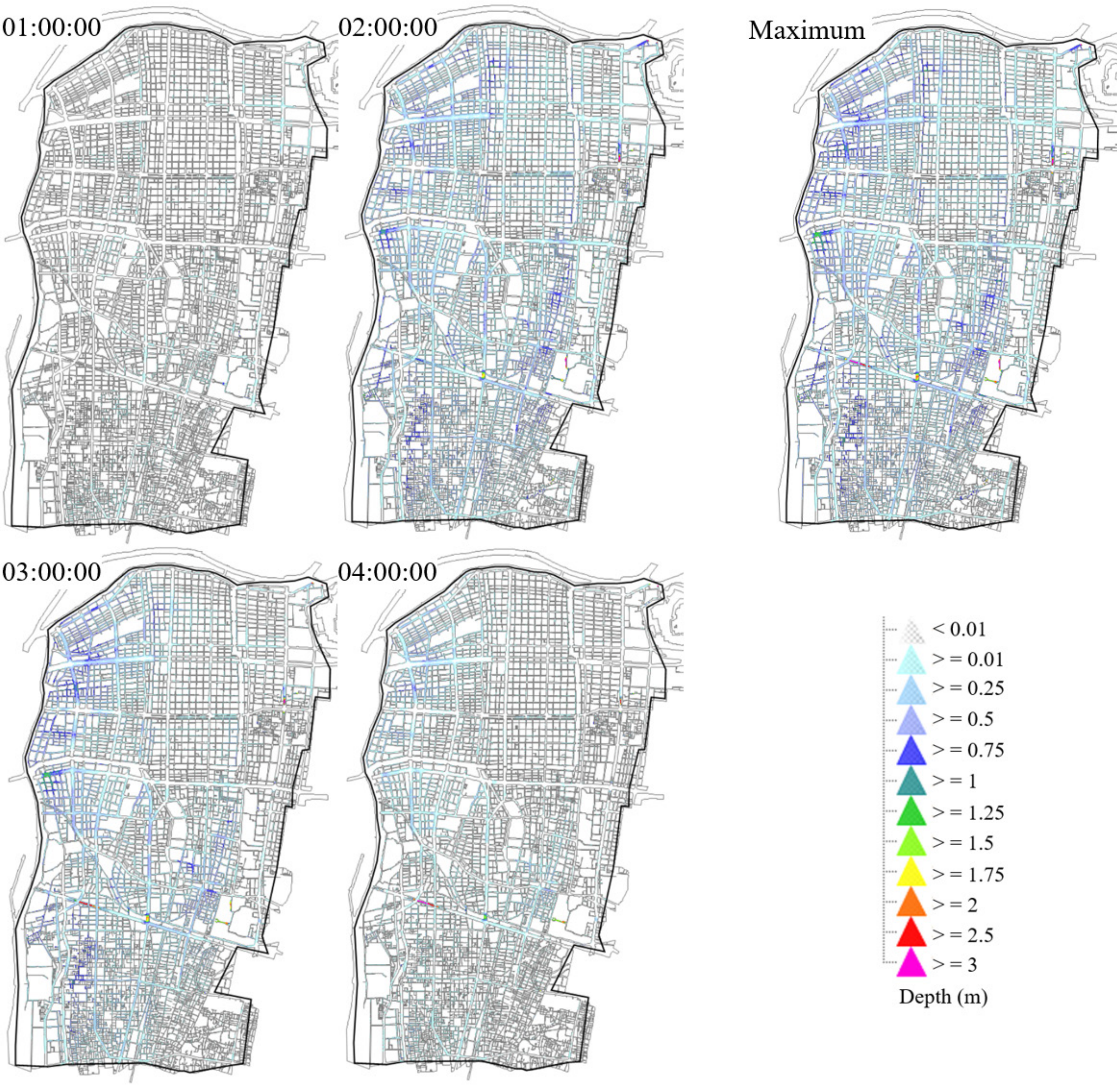


Figure 5. Inundation process and maximum depth

## 4. INFLOW CHARACTERISTICS INTO UNDERGROUND SPACE

### 4.1 Subway

Table 1 shows the inflow characteristics of flood water in each underground space. The results show that, 24 subway stations were flooded. Inflow occurred at 84 entrances, and the total inflow into the station was 280,123m$^3$. Awaza Station had the largest inflow of 90,636m$^3$, which is about 32% of total volume into the subway stations. Others volume was 31,991m$^3$ at Honmachi Station, 25,560m$^3$ at Ebisucho Station, 16,629m$^3$ at Daikokucho Station, 16,037m$^3$ at Hanazonocho Station, 14,031m$^3$ at Tengachaya Station, and 11,467m$^3$ at Nishinagahori Station. The top six stations with the largest inflows accounted for 74% of the total. Figure 6 shows the inflows at the six stations where the total inflow exceeded 10,000 m$^3$. Peak inflow times are different at each station. In particular, at Awaza Station, Nishinagahori Station and Sakuragawa Station, the peak of the inflow occurred about 1.3 hours after the rainfall peak, and the inflow peak was about 50 minutes behind other stations. The area around 3 stations is below or less than 1 m above sea level, thus peak time was slowed by floodwater flowing from other areas. It indicates that channelization of roads is occurred. Furthermore, the risk of inflow is high at Osaka Metro Awaza Station because the inflow continued for about 2 hours after the rainfall ended.

Table 1. Inflow characteristics into underground space

| Station | Inflow point 1) | Peak inflow ($m^3$/s) 2) | Peak time 3) | Total inflow ($m^3$) |
|---|---|---|---|---|
| Yodoyabashi (A) | 3 (11) | 0.96 | 2:02:00 | 5,106 |
| Hommachi (B) | 15 (22) | 2.13 | 2:01:00 | 31,991 |
| Shinsaibashi (C) | 1 (7) | 0.19 | 1:40:00 | 54 |
| Namba (D) | 4 (30) | 0.74 | 2:21:00 | 4,730 |
| Daikokucho (E) | 4 (6) | 1.95 | 2:01:00 | 16,629 |
| Dobutsuen-mae (F) | 5 (8) | 1.05 | 2:11:00 | 9,987 |
| Sakaisuji-Hommachi (H) | 4 (15) | 0.22 | 1:40:00 | 960 |
| Nippombashi (J) | 2 (7) | 1.12 | 2:01:00 | 3,585 |
| Ebisucho (K) | 7 (7) | 1.57 | 2:15:00 | 25,560 |
| Tengachaya (L) | 1 (2) | 2.82 | 2:05:00 | 14,031 |
| Awaza (M) | 9 (10) | 3.39 | 2:49:00 | 90,636 |
| Nishinagahori (N) | 4 (9) | 1.07 | 2:49:00 | 11,467 |
| Sakuragawa (O) | 2 (6) | 0.46 | 2:50:00 | 3,596 |
| Tanimachi 9-chome (P) | 1 (9) | 0.01 | 1:42:00 | 16 |
| Tanimachi 4-chome (R) | 1 (12) | 0.02 | 1:40:00 | 50 |
| Shitennoji-mae Yuhigaoka (T) | 1 (5) | 0.05 | 1:40:00 | 58 |
| Higobashi (U) | 3 (11) | 0.69 | 2:01:00 | 3,319 |
| Yotsubashi (V) | 3 (6) | 0.50 | 2:13:00 | 3,960 |
| Hanazonocho (W) | 5 (5) | 1.10 | 2:10:00 | 16,037 |
| Kishinosato (X) | 3 (3) | 0.42 | 2:05:00 | 2,679 |
| Nishiohashi (Y) | 1 (5) | 0.01 | 2:05:00 | 10 |
| Yodoyabashi (Keihan) (A1) | 1 (10) | 0.03 | 1:41:00 | 38 |
| Kitahama (Keihan) (B1) | 1 (9) | 0.14 | 1:40:00 | 194 |
| Sakuragawa (Hanshin) (D1) | 3 (4) | 0.43 | 2:46:00 | 2,937 |
| Crysta Nagahori (a) | 3 (31) | 0.09 | 2:06:00 | 212 |
| Namba Walk (b) | 2 (29) | 0.28 | 1:45:00 | 1,004 |
| Namba Nannan (c) | 2 (11) | 0.19 | 1:43:00 | 437 |
| Tanimachi parking lot (①) | 1 (4) | 0.01 | 1:40:00 | 9 |
| Tosa-bori parking lot (②) | 2 (4) | 2.02 | 2:03:00 | 11,589 |
| Azuchi-cho parking lot (③) | 2 (2) | 1.53 | 1:41:00 | 7,930 |
| Honmachi parking lot (④) | 1 (1) | 0.01 | 2:04:00 | 7 |
| Utsubo parking lot (⑤) | 2 (2) | 4.03 | 2:46:00 | 49,601 |
| The east Nagahori parking lot (⑦) | 2 (2) | 1.07 | 2:03:00 | 3,234 |
| Ueshio parking lot (⑨) | 1 (2) | 0.20 | 1:40:00 | 329 |

1) The number of entrances at each station is shown in parentheses.
2) The value of the entrance with the largest peak inflow is shown.
3) The time shown is the calculation time.
※ The following 10 points are not shown because there was no inflow.
Kitahama (G), Nagahoribashi (I), Temmabashi (Q), Tanimachi 6-chome (S), Matsuyamachi (Z), Temmabashi (Keihan) (C1), JR Namba (E1), Nagahori parking lot (⑥), Shiokusa parking lot (⑧), OCAT parking lot (⑩)

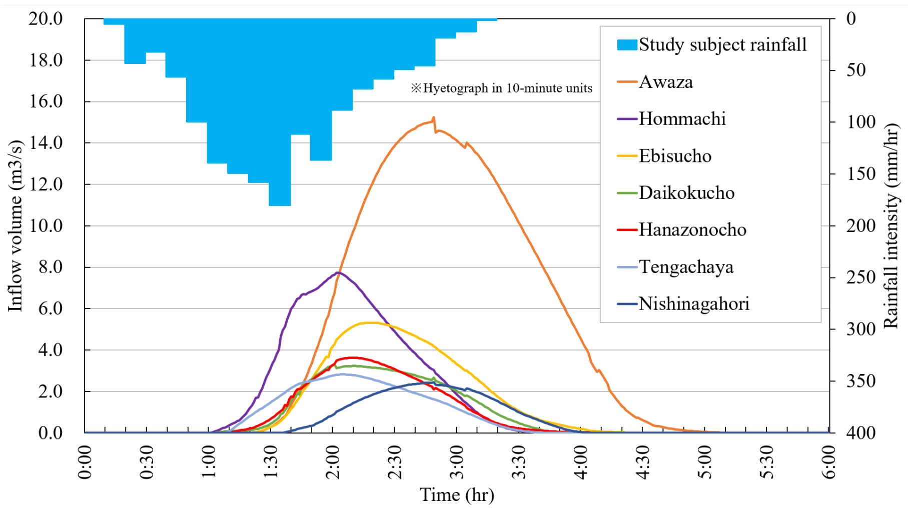


Figure 6. Inflow to subway stations where the total inflow exceeded 10,000$m^3$

4.2 Underground mall

The total inflow into the underground mall was 1,653m$^3$. It was the smallest inflow in the underground space. However, inundation occurred at Namba Station and Nippombashi Station, where Namba Walk and NAMBA Nannan are connected on the same floor level. Therefore, subway inundation may affect the underground mall. When local heavy rain would occur in a short time, it is suggested that the inundation risk in the underground mall around Namba is high. At Crysta Nagahori, it is suggested that the inundation risk is lower because the inflow of the connecting subway station was small.

4.3 Other underground space

In this study, underground parking lots and underpasses managed by Osaka City were modeled. The results show that, floodwater flowed into 7 underground parking lots, and the total inflow was 72,699m$^3$. It is considered that the total inflow was large because the Utsubo and Tosa-bori parking lots were located in the northwestern part of study area where the inundation depth was more than 1m. Figure 7 shows the inundation depth of underpass. The total inflow into the underpass was 22,356 m$^3$. The underpass inflow strart time was the fastest of all underground spaces. If a car is submerged, the escape depth limit for adult men is 0.56m (Takahashi et al,2013). At the underpass, the water depth exceeded the escape limit water depth in about 50 minutes from the start of rainfall. Therefore, it is suggested that early evacuation during inundation becomes important in underpass.

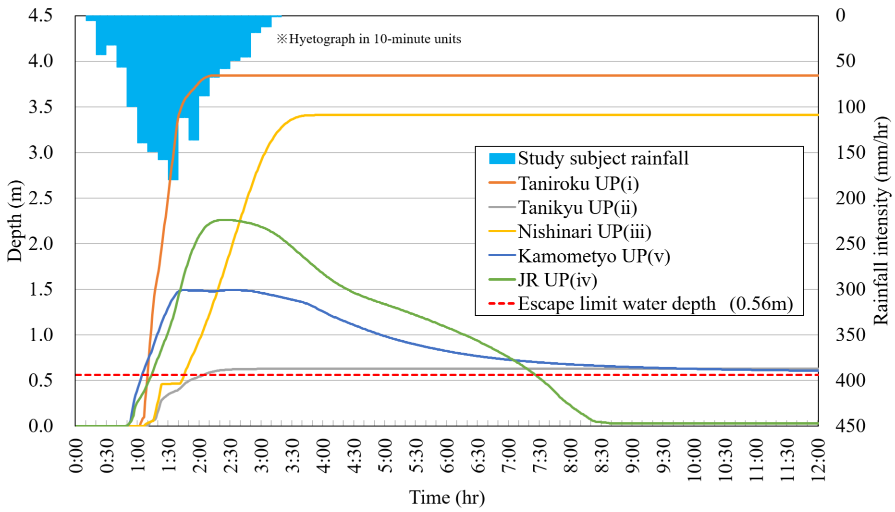


Figure 7. Inundation depth of underpass

## 5. CONCLUSIONS

In this paper, a simulation model considering sewerage drainage system in Tsumori treatment area in Osaka city was built. Underground entrances were modeled on the basis of field survey results. Numerical results show that the inflow rate of the flood water was 6.04% in subway, 0.04% in underground mall, 1.57% in underground parking, and 0.48% in underpass. In particular, Osaka Metro Awaza Station has a high risk of inflow. In the future, the behavior of flood water in mega-underground space during pluvial flooding in Tsumori treatment area will be investigated.

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