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Inundation Process of Underground Space in Highly Urbanized Area

INUNDATION PROCESS OF UNDERGROUND SPACE IN HIGHLY URBANIZED AREA

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ABSTRACT

Inundation process in the underground space as well as on the ground surface in the highly urbanized area in Tokyo was studied numerically. Recently, a relatively heavy rainfall or a thunderstorm arises in the late afternoon in summer season. We also experienced a serious rainstorm which was brought by a typhoon in Japan. The maximum intensity of local rainfall grows higher and it is possible to exceed the designed intensity of it for drainage networks, which is probably because of a global warming. Therefore, we must have the information about the expected state of inundation especially for the area which is connected to the underground space. The objectives of this study were to (1) develop the numerical model to evaluate the inundation process, (2) apply it to the highly urbanized area of downtown Tokyo in order to evaluate the expected state of inundation, (3) develop an evacuation model of persons from the underground space to a ground level, and (4) find out the possible routes for evacuation.

Keywords: inundation process, underground space, evacuation model, highly urbanized area.

1. INTRODUCTION

The environment in urban area grows worse recently. Especially in summer season in Tokyo, the heavy rainfalls whose intensity is much higher than the designed intensity for drainage network occur in several times a year, which probably arise from so-called heat-island phenomenon and global warming. In the present study, the highly urbanized area of downtown Tokyo was the objective to be investigated. Only buildings or paved roads exist and there is no vacant land in the area. If the rainfall event occurs, the supplied water flows either on the paved roads or in the drainage pipes. In such a highly urbanize area, the weakest point in inundation is the relatively lower place on the road network. If the underground space is in such a place, the space is most dangerous and has the possibility to be inundated. As a matter of fact, there exists a compound underground space which consists of a shopping mall and a subway station in this study area, and actual damage was reported in the underground space in 1999. But passers-by of this underground space and the manager do not necessarily have enough information about this. Therefore, we now have to investigate the inundation potential and the expected state of inundation there. In addition to this, investigation about the evacuation strategy is also needed to reduce the human damage in case of emergency due to inundation. Considering the above, the numerical model was developed, and a series of numerical simulation were conducted in this study.

Recently the inundation process in underground spaces was studied by some researchers (Toda and Inoue et al., 2004; Aihata and Toda et al., 2005; Sekine and Kawakami, 2005a, 2005b). On the other hand, we have few studies on the evacuation from an inundated underground space, one of which was done by authors (Sekine and Motoyama, 2008).

2. SUMMARY OF THE NUMERICAL MODEL

2.1 Detailed information about the area, underground space and rainfall

Investigation was conducted in highly urbanized area in Shibuya District, Tokyo. Figure 1(a) denotes the summary of this area. In Figures 1(b) and 1(c), the road network and the drainage network are seen. The bold red lines in Figure 1(a) represent the boundary of this computational domain, and are set along the relatively higher places or a median strip of road. In this study area, there is no vacant space, and only buildings and paved roads are there. The rainwater which was supplied on roads was only considered here, while the water supplied in the area which was almost occupied by the buildings was not taken into account. The rainwater onto a building is temporarily stored in its own facilities and is discharged to drainage pipe a few hours later. This means that the effect of neglecting the water in building area is not so important to evaluate the state of inundation against the localized torrential rain. The topographical characteristics of the study area can be summarized as follows: (1) the ground surface elevation is lower in the central portion of the area, and the depressed lowest area (see the yellow coloured area in Figure 1 (a)) exists around "S station", (2) there are several downhill slopes there which are directed toward the lowest portion. This means that the rainwater tends to flow down and converge to the depressed area around the station.

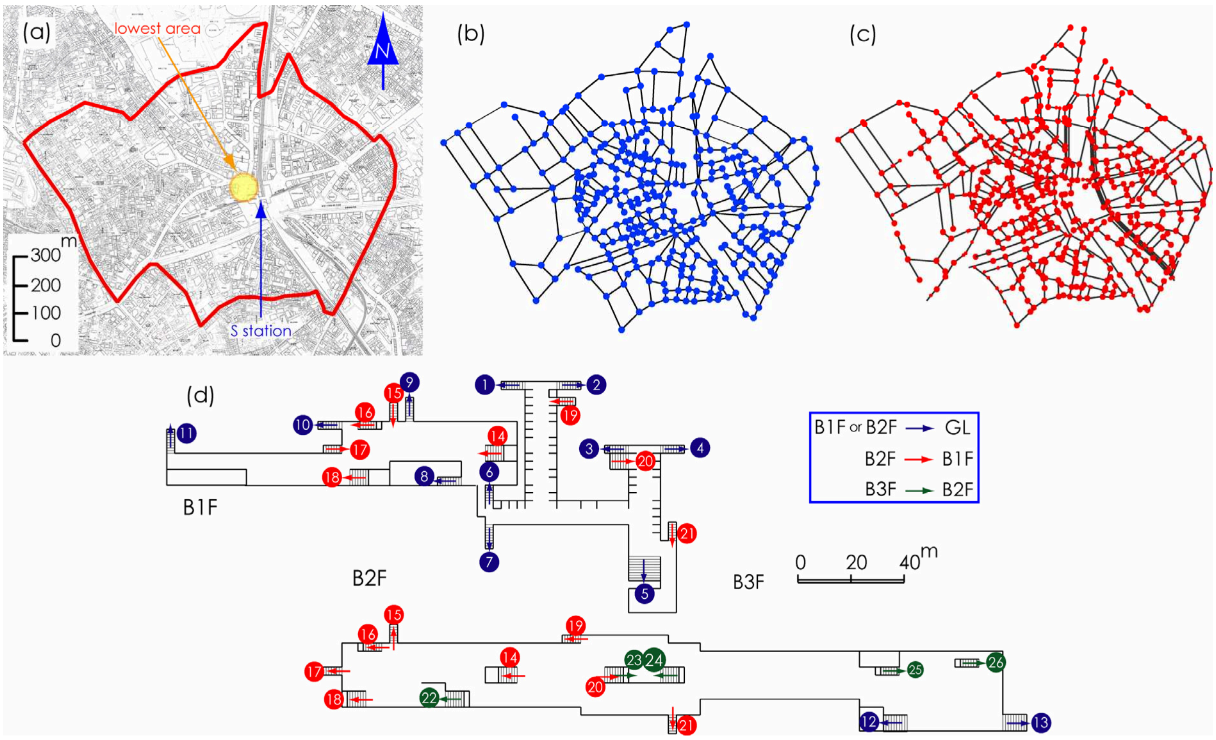

Figure 1 Summary of the study area and the underground space: (a) a computational domain, (b) the road network, (c) the drainage network and (d) the plain view of underground space.

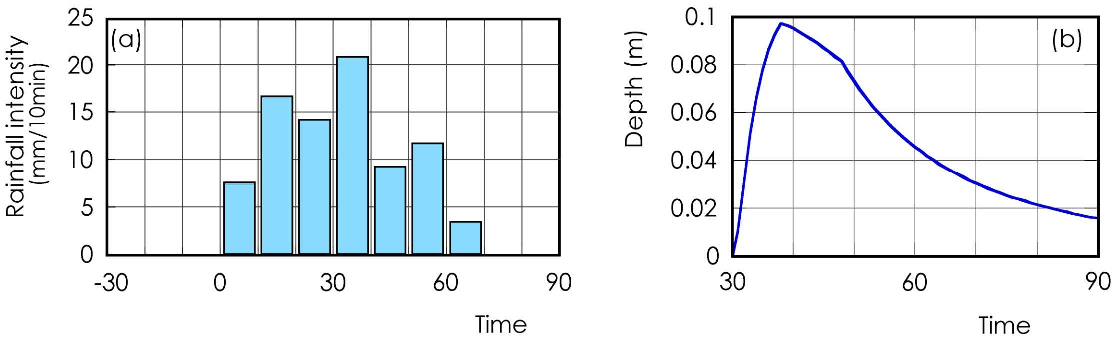

Figure 2 Input hyetograph of rainfall (left) and the computational result of water depth at the entrance gate No.6 and 7 to the underground space (right).

It is noted that the underground shopping mall and the subway station locate below the ground surface in the yellow coloured portion in Figure 1 (a). If the depth of inundated water on road is larger than 0.4 m in the vicinity of the gate for underground space, the water flows into the underground space. Figure 1(d) shows the plane view of this underground space, which is a “triple-decker”. The first basement (B1F) is a shopping space with some partition walls and the second basement (B2F) is a concourse space, and the third basement (B3F) is the platform of subway station. The arrows shown in Figure 1(d) denote the direction of down stairs. As a result of this study explained later, only two gates and stairs No. 6 and 7 are the possible ones that the water can pass through and comes into the underground space.

The actual rainfall data, which was measured in this area on September 29, 1999, was adopted to evaluate the state of inundation. Figure 2 shows the hyetograph of rainfall. As a reference, the value 50 mm/h is the designed intensity for the drainage system there, and therefore the underground space actually experienced inundation. It is obvious that this rainfall event is classified as a localized torrential rain.

Main stream of persons, who move around this underground space, is from the subway station to the JR station which located on ground level, and vice versa. Therefore, a person takes the stairs No.23 or 24 from B3F to B2F, No.21 from B2F to B1F and No.5 from B1F to ground level as a typical usual route.

2.2 Inundation model in highly urbanized area

Numerical model of inundation in this study was constituted by several sub-models on (1) the surface flow on roads, (2) the flow in the drainage pipes, (3) the water exchange in a “storage tank” (or street inlet) along the side of roads, which works as a buffer between a water on road and that in pipe, (4) the flow in underground space. Evacuation model from underground to ground level was also developed. The details of each model are explained below.

Inundation of the ground surface was simulated only on the road network shown in Figure 1 (b). Figure 3 is the definition sketch of the control volume for this computation. Computational nodes were placed on the crossings of roads, and the control volume was set around each node. The test sections were placed on the roads in the middle of the adjacent nodes. Velocities v_n, v_s, v_e, v_w and the corresponding flow discharges Q_n, Q_s, Q_e, Q_w were evaluated at each test section. In Figure 3, green lines denote drainage pipes, and the red boxes denote the “storage tanks”. The distance of road between each node, the width of each road B and the ground elevation at each node or crossings η are all known. Governing equations of the flow on roads are as follows;

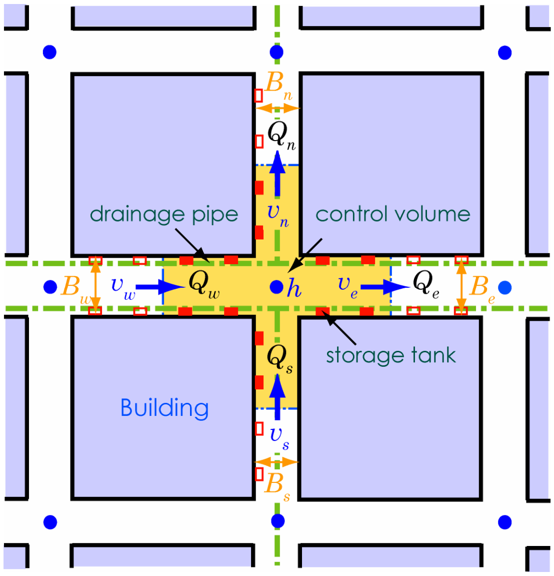

Figure 3 Definition sketch of control volume in flow computation on road network

$$A\frac{\partial h}{\partial t} = -(Q_n - Q_s) - (Q_e - Q_w) - Q_{ST} - Q_{UG} \tag{1}$$

$$\frac{1}{g}\frac{\partial v}{\partial t} = -\frac{\partial}{\partial x}(\eta + h) - \frac{\tau_o}{\rho g h}\ ; \quad \tau_o = \frac{\rho g n^2}{h^{1/3}} v^2 \tag{2}$$

in which h = flow depth, n = Manning's roughness coefficient, τ_o = shear stress on road surface, A = area of the control volume, Q_{ST} = sum of the discharge by which the water on road flows into each storage tank in this control volume, and Q_{UG} = discharge by which the water flows into the underground space if possible. The flow depth was calculated on the basis of volume conservation principle. In this computation, the convective terms in the equation of motion are neglected for simplicity.

Basic idea of the computation of flow in the drainage pipes is almost same as that described above for the surface flow on roads. The computational nodes were placed on the junctions of drainage pipes, as is seen in Figure 1(c). The difference between an actual drainage network and the reproduced one is only on the shape of drainage pipe. The square pipe with the same cross-sectional area was adopted for simplicity in this analysis instead of actual circular pipe. A "slot model" (Chaudhry, 1979) was adopted here.

The effect of "storage tank" was taken into account hydraulically in this analysis. As we have studied in the class of Hydraulics, the depth in this tank was evaluated numerically on the basis of the relation of volume conservation. Such tanks are placed along the both side of a road every 20 m in this study area. The tank is the cylinder whose diameter is 50cm and height is 80cm, and is connected to the drainage pipe by a circular pipe of 0.2 m in diameter. The upper edge of the tank is left open to the air, even though the metal mesh screen covers on it. The number of the tanks in each control volume was not necessarily an integer, and was set as the value of total length of roads in a control volume divided by the interval of 20 m in this analysis.

The computation of the flow in underground space was the two-dimensional one. In this study, the first and second basements were covered by the computational grids whose size was 3 m in both x and y direction, and the flow on each floor was analyzed. The third basement, on the other hand, was treated just like a pond, and only inflow of water to this space on the platform of the subway station was computed through the stairs. Basic idea of this analysis is same as the one described above. The boundary condition is as follows; the velocity components on the solid walls are vanished in both normal and tangential directions to the wall. The flow on the stairs was analyzed with considering the relation between a local flow depth and the height of each step.

2.3 Evacuation model in underground space

The evacuation model of persons was developed in this study by taking into account the knowledge in the field of human science and engineering, ophthalmology and some more else. Fundamentals of the evacuation behaviour of person are summarized as follow. The coordinate of each person at a give time (x_p, y_p) is evaluated by

$$(x_p, y_p) = (x_o, y_o) + v_p \times (\cos\theta, \sin\theta) \times \Delta t \tag{3}$$

in which v_p = walking speed of a person, θ = moving angle of evacuation, (x_o, y_o) = the coordinate of the person infinitesimal time interval Δt before then. The walking speed v_p depends on the density of crowd ρ_c which is defined as the number of persons per unit area of the floor. If ρ_c is less than unity, one can move freely without any disturbances by others and the averaged speed is almost 1.3 m/s. If ρ_c is larger than unity, on the other hand, the speed is not independent of ρ_c, and it can be estimated by following relations:

$$v_p = 1.3 - 0.4 \times \rho_c\ (1 \le \rho_c \le 3);\ \ v_p = 0.1\ \ (3 \le \rho_c \le 7);\ \ v_p = 0.05\ \ (7 \le \rho_c) \tag{4}$$

The value must be reduced according to a flow depth if one walks on a floor of inundated space. The angle θ is determined so that a person moves in the direction of local destination. If someone finds the sign of evacuation direction, one starts to move in the direction. If someone can see the upward stairs, one tries to move there. In this study, the best route of evacuation in whole domain of this space was tried to find. This means that the local destination all over this space is specified intentionally so that the all persons who stay there can evacuate safely and efficiently to the ground level. When we move in some direction, there is the tendency that we try to avoid passing through a crowded area and make a slight detour. Before determining the angle θ, such a tendency was also taken into account in this simulation.

Another important issue is the judgement when a person starts his evacuation behaviour. In this model, a person is made to start to move when he recognizes the water approaching to him or the other person passing him by in the direction of local destination. The distance beyond which one can not recognize the water is set as 5 m on the basis of the knowledge in the field of ophthalmology.

2.4 Some conditions

In this study, dry bed conditions were applied as the initial condition in computing the flow on road, in drainage pipe and on the floor of underground space. Water depth in each storage tank was zero initially. Due to this treatment, the expected inundation damage must be underestimated to a certain extent. Model parameters to be specified in this numerical model are Manning's roughness coefficients. The value on road surface is set as 0.05, the one in drainage pipes is 0.013 and that on the floor of underground space is 0.02, respectively. These values have been checked through a series of computation. However the validity of them has not been confirmed yet in the strict sense, because we did not have enough measured data in literature.

In this simulation, actual data on road network, drainage network and the underground space were used, and the database about them was prepared before computation.

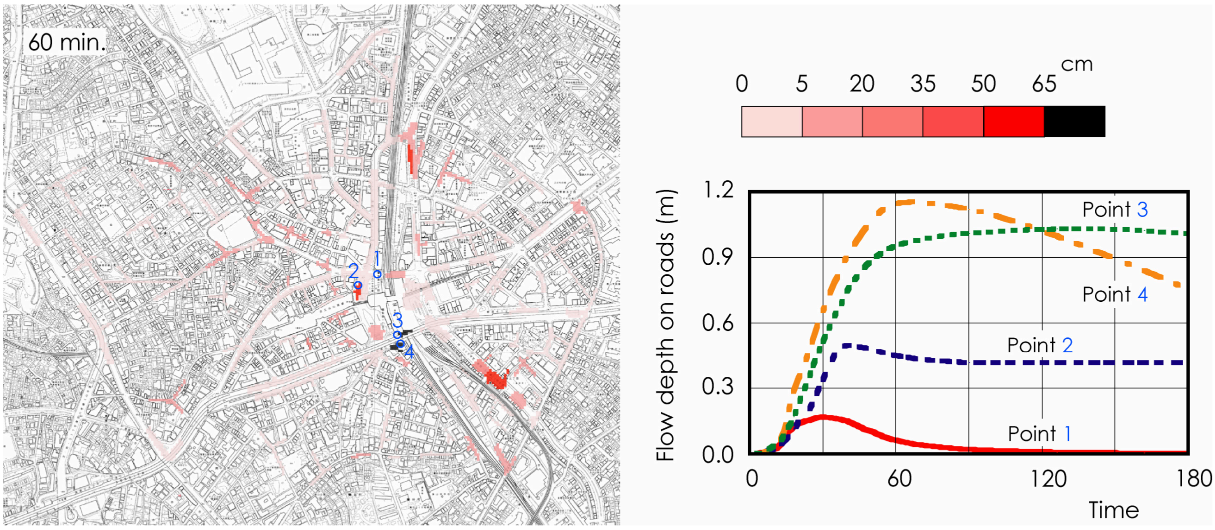

Figure 4 Flow depth on roads: contour map of depth on roads at 60 minutes from the beginning of the rainfall event (left), the temporal variation of it at each local point (right). Point 2 lies in the vicinity of the gate No.6 and 7 of underground space.

3. RESULTS AND DISCUSSION

3.1 Inundation process on the surface of road network

Inundation process on the surface of the roads is discussed here by referring to the computational results. Figure 4 denotes the contour map of water depth at 60 minutes from the beginning of rainfall event. At this moment, the volume of inundated water reached almost maximum value. In Figure 3, the temporal variations of flow depth at 4 points are seen. One can easily understand that the following two restricted areas have the problem of inundation. One is the area around the "under-pass" of railway, and Points 3 and 4 in Figure 4 locate there. Flow depth in this area reached more than 1.0 m, which means that the serious traffic jam arises on road in this area. The other is the area around Point 2. In this area, there exit two gates toward the underground space whose numbers are No.6 and 7 in Figure 1 (d). If the depth grows larger than 0.4 m at point 2, the water can pass through the gate and come into the underground space. This result in the most serious damage we can expect in this study area. In figure 2 (b), the temporal variation of water depth at the top of the stairs No.6 and 7 was seen. The value of the depth corresponds to that of the depth at Point 2 in Figure 4 subtracted by 0.4 m.

3.2 Inundation process in underground space

It was expected that the water on road flows into the underground space through the gates and stairs No.6 and 7 if we really have such a rainfall as is seen in Figure 2 (a) again and also we do not take any measures to deal with the situation. Therefore, we need some information about the inundation process in this underground space. Figure 5 shows a time series of contour map of water depth on the floor of the first and second basement. One can see the spreading pattern of the water in this space. It should be noted that the torrential streams occurs on the stairs even if the water discharge is restricted. One can also find that each stairs reaches such a state at different time. This means that we can find the safe evacuation route on stairs without any water. Under the condition of this simulation, the maximum water depth in this space is less than 0.1 m. This means that the damage will not be so serious and the adult persons who stay there can come back to the ground level if they move in good order. Children, the person of advanced age or the handicapped person, on the other hand, need some guide or help before they can escape from this circumstance. In such an underground space, it is desirable that the evacuation route is found and the evacuation strategy which enables the persons to reduce their risk is established.

3.3 Discussion about the evacuation route

In this study, several series of numerical simulation of evacuation was conducted. The results of three cases under the different conditions were discussed here. In case 1, a person moves in the direction of nearest stairs and goes up to the ground level without any guidance. In case 2, the announcement is made over the speaker system, and the persons there are forced to start moving in the same direction as was explained above. Case 3, on the other hand, is the best pattern of evacuation we found in this underground space, which is recommended in this

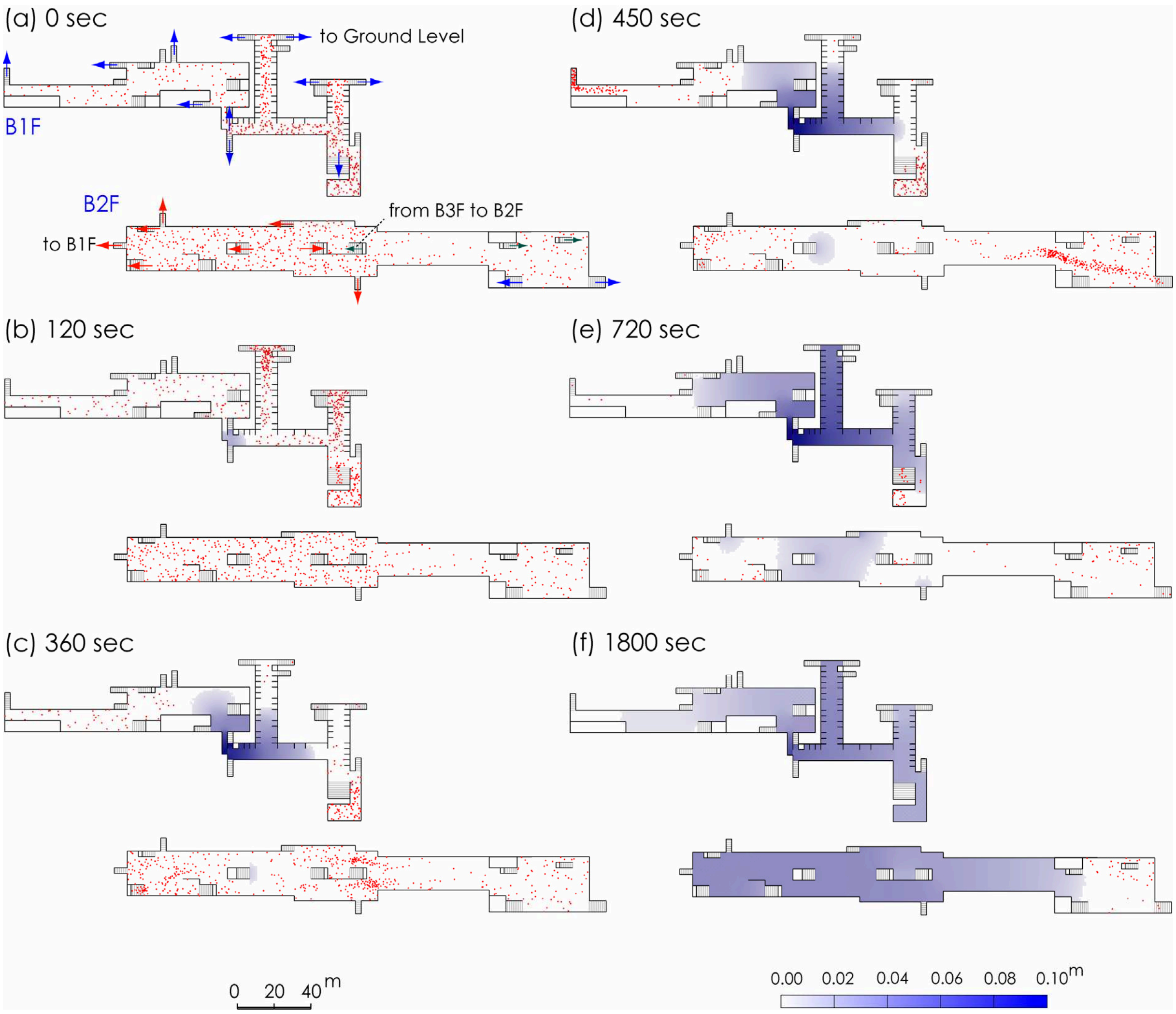

Figure 5 Contour map of inundation depth in underground space and the pattern of evacuation at each time: the origin of time is 30 minutes from the beginning of the rainfall event. Each red dot denotes the position of an individual person.

study. In case 3, the persons on B2F are guided to go up the stairs of No. 13 and 18 only (see in Figure 1 (d)). Figure 5 denotes the typical pattern of evacuation of persons in Case 3. In this figure, each red dot denotes the position of each person. The number of the persons is totally one thousand, and half of the persons are on B1F and the other half were on B2F. The initial position of each person was set by using a random number generator. The pattern of evacuation in each case can be summarized as follows. In case 1, all the persons can reach the ground level without any serious risks though the density of crowd takes a larger value on several stairs and the value attains frequently about 10. It is possible that the persons fall over like a file of dominoes on the stairs. In case 2, the evacuation can be completed only for about 170 sec, but the density of crowd on each stairs increases much more than that in case 1. Such an announcement should not be made because the persons encounter more difficulties. In case 3, on the other hand, no problem was found though the density of crowd grows sometimes a large on the floor not on the stairs. One can evacuate safely and efficiently in this case because the persons who start moving from each basement are not necessarily mixed in this space. And it is obvious that the state of jam on the stairs is much improved.

4. CONCLUSION

Numerical model of the inundation process in highly urbanized area was developed in this study. Numerical computation was conducted to evaluate the state of inundation expected in such area in Shibuya District, Tokyo against the actual rainfall. It was obvious that there is a possibility that the inundation occurs in underground space there if we do not take any measures to deal with the situation. The spreading pattern of inundated water in this space was also understood. In addition to the analysis of inundation, the evacuation model of persons from this underground space to the ground level was also developed in this study, and a series of numerical simulations were conducted. As a result, the best evacuation route and the strategy in case of this underground space were discussed.

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