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CRITERION AND ITS APPLICATION FOR SAFETY EVACUATION DURING UNDERGROUND FLOODING

By

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SYNOPSIS

In recent years, very heavy rainfalls of above 50 or 100mm/hr have hit urban areas in Japan, causing flood to flow into underground spaces such as underground shopping arcades, subway stations and basement of buildings. Heavy rainfalls that hit Tokyo, Nagoya and Fukuoka caused the underground inundations. Such urban floods have been increasing in recent years. When the underground inundation occurs, people must evacuate to the ground as soon as possible. Therefore, it is necessary to evaluate when and where it becomes difficult for people to evacuate during the inundation. To prepare for evacuation plans in the situation, it is necessary to determine the evacuation criteria for safe evacuation. In this paper, the evacuation criteria obtained by using real size models of stairs and corridors are discussed. It was found that evacuation speeds depend on flow velocity and water depth. Considering the two parameters, momentum and specific force of flow are investigated as a criterion for safe evacuation. We concluded that the specific force per unit width, $u^2h/g+h^2/2=0.125$, is a good criterion for safe evacuation, where u=flow velocity, h=water depth and g=the gravity acceleration. Furthermore, the criteria was tested in an underground space in Kyoto, Japan by using simulation data of inundation with 2D shallow flow model.

INTRODUCTION

Many Japanese cities located on alluvial plains are prone to floods every year. Such cities are fully urbanized and have underground shopping arcades and subway stations. These underground spaces are also in flood-prone areas. Recent urban floods such as Fukuoka flood in Japan in 1999 and Seoul flood in Korea in 2001 have induced inundation into underground space and caused heavy damage. Therefore, it is important to examine the inundation and evacuation system in underground space from the view points of the hydraulics and disaster prevention.

Such urban floods have been investigated by using numerical models (e.g. (1),(2),(3),(4)). However, there are not enough data to verify these models. In order to obtain precise data for the improvement of numerical models and to investigate the behaviour of flood flow in urban areas with underground space, hydraulic model tests by using a city model with 1/100 scale and an underground-space model with 1/30 scale have been performed (5). Then a two dimensional shallow flow model with unstructured mesh and a storage pond model were applied and verified by using experimental data (6), (7). From the results, it was found that is very difficult to evacuate through staircases during floods. Evacuations from underground space were investigated by using a real size model of staircase, and evacuations from basement were also tested by using a real size model of door (8), (9).

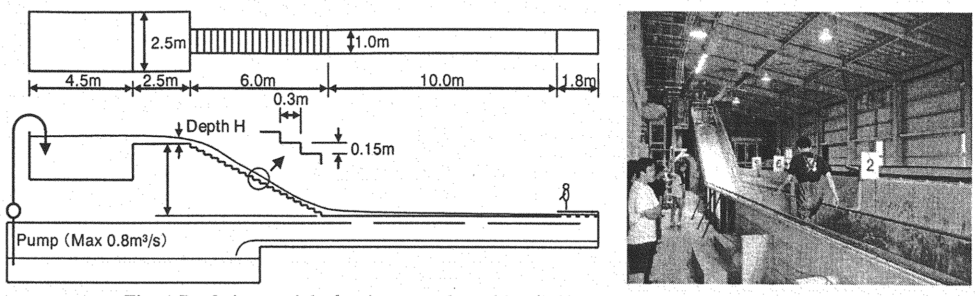

Fig. 1 Real size model of staircase and corridor (left) and a photograph of evacuation test along the evacuation route (right). There are 20 steps and 10m long corridor.

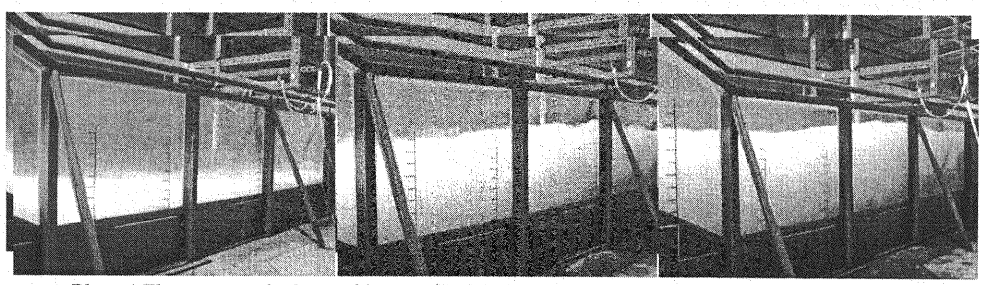

Photo 1 Flow patterns in the corridor part (H=0.3m). Photographs in a normal case (left, z=0.0m), a dam-up case (middle, z=0.2m) and another dam-up case (right, z=0.3m).

Table 1 Water depth, flow velocity and evacuation speed along the corridor.

Depth H (m)	Height of end plate z (m)	Corridor depth (m)	Flow velocity (m/s)	Evacuation speed (m/s)
0.2 (normal)	0	0.053	2.64	1.14
0.2 (dam-up)	0.3	0.488	0.30	0.65
0.3 (normal)	0	0.076	3.54	1.04
0.3 (dam-up)	0.2	0.432	0.62	0.78
0.3 (dam-up)	0.3	0.570	0.47	0.71

In this paper, the criteria for safe evacuation from underground space are discussed. On the route of evacuation, there are three point to consider. The first point is whether the basement doors can be opened or not. The second point is whether people can walk through flooded corridors. And the third point is whether they can go up stairs. These points are concerned with water depth, h, and flow velocity, u. From the results of our previous studies, it was found that 0.4m is the limit depth in front of the door to be opened, and that the momentum of flow, $u^2h=1.2$, is an criterion of safe evacuation through stairs. The value of momentum can be applied to the examination of the evacuation through stairs. However, it is not an appropriate criterion for the second point. As the flow velocity on corridors is low or nearly zero, the momentum shows very small value. If the value of specific force (momentum) is used as a criterion, both of the flow momentum and the hydrostatic pressure can be considered. In this paper, this criterion is discussed on the basis of evacuation test data by using real size models of stairs and corridors. As the two criteria of safe evacuation were obtained, they were tested by using calculated data in the case of an underground space.

EVACUATION TESTS

To simulate the real flow over a staircase, a real size model of staircase was assembled as shown in Fig. 1. There are 20 steps of which tread is 0.3m and riser is 0.15m and the total height is 3m in the stair part. The length of corridor is 10m and the width is 1m. Flow discharge is up to $0.8m^3/s$. Evacuation tests were conducted by using this real size model. H is the water depth on the ground level. To simulate the submergence of the corridor section, end plates were placed at the end of the model. A case without end plates is called a normal case and a case with end plates is a dam-up case as shown in Photo 1. The three photographs show the flow patterns in the three case of H=0.3m listed in Table 1. The flow and depth in the normal case are quite different from those in dam-up cases. The data obtained in the previous studies (8), (9), are also shown in this paper.

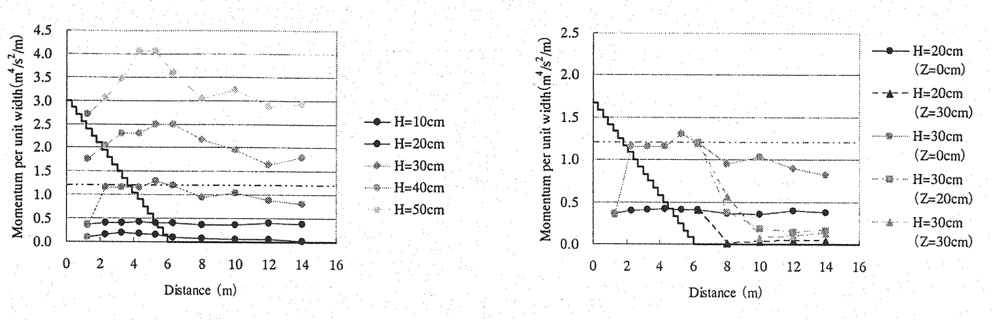

Fig. 2 Distributions of momentum per unit width along the evacuation route in normal cases (left) and dam-up cases (right). Chain double-dashed lines are the evacuation criterion of $u^2h=1.2$.

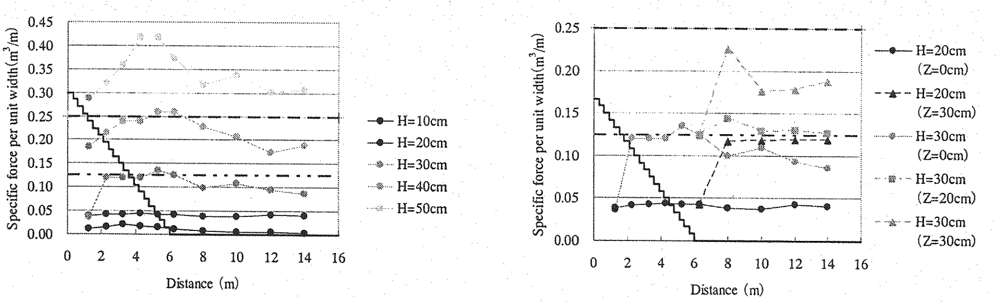

Fig. 3 Distributions of specific force per unit width along the evacuation route in the normal cases (left) and the dam-up cases (right). Chain double-dashed lines are the criterion of $u^2h/g+h^2/2=0.125$ for safe evacuation and the dashed lines are the limit value=0.250 for evacuation without any help.

Examinees of the evacuation test were composed of 47 females and 257 males. Mean ages were 30.2 and 25.8 years old respectively. Evacuation time, when an examinee walked up through 10m landing and 20 steps of staircase, was measured under the conditions of five water depth cases from H=0.0m to 0.4m. A lifeline was used for the examinee's safety in the cases of H=0.3 and 0.4m and handrails were installed on both sides for emergency cases. Two percent of males and 34 percent of females used handrails in the case of H=0.3m, and 13 percents males and 78 percents females used the handrails in the case of H=0.4m. These results confirmed that the previous conclusion that the limit depth for safe evacuation is H=0.3m (4), (5), and implied that the limit depth of evacuation is H=0.4m.

CRITERIA FOR SAFE EVACUATION

Water depth, flow velocity and evacuation speed along the corridor are listed on Table 1 for normal and dam-up cases. Evacuation speed becomes slower in the cases of fast flow velocity and deep water. This shows that the evacuation speeds depend on not only flow velocity but also water depth. In addition, examinees said that they felt strong hydrostatic pressure acting on their feet in the deeper cases. Considering the results, it is assumed that criteria for safe evacuation include water depth, h, and flow velocity, u. Two criteria can be considered as follows: momentum per unit width, u^2h, and specific force per unit width, $u^2h/g+h^2/2$, where u=flow velocity, h=water depth and g=the gravity acceleration.

Fig. 2 shows the distribution of momentum per unit width along the evacuation route for normal cases and dam-up cases. In the previous study (8), it was proposed that H=0.3m and $u^2h=1.2$ are the criterion for safe evacuation. This criterion is applicable in the normal cases, but this is not good for the dam-up cases. This value is not applicable in the corridor section, because the magnitude of the momentum becomes very small due to low velocity. On the other hand, specific force does not become small along the corridor in the dam-up cases as shown in Fig. 3. From the results, it was found that the appropriate value of specific force per unit width for safe evacuation is 0.125 of double-dashed line in Fig. 3. This is equivalent to the value of the momentum, $u^2h=1.2$ (H=0.3m). As the specific force is applicable in both normal and dam-up cases, this criterion is better for safe evacuation. In addition, it can be concluded that the limit value of evacuation without any help is 0.250 of dashed line in Fig. 3, which can be also estimated with the data of H=0.4m. The evidence for this reasonable value is that 13 percent of males and 78 percent of female examinees could not evacuate without holding on to the handrails during their evacuation tests in the case of H=0.4m.

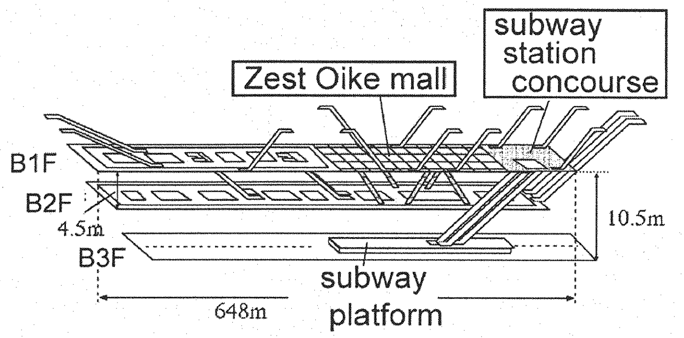

Fig. 4 Structure of underground space in Kyoto, Japan.

Table 2 Inflow conditions through entrances on the ground.

Entrance No.	Inflow time	Inflow discharge (m^3/s)	Depth on the ground (m)
1	00m00s	1.58	0.60
15+16	06m18s	14.08	1.02
3	10m03s	1.32	0.33
5	10m14s	2.13	0.46
4	10m30s	1.88	0.42
2	10m47s	2.63	0.53
18+19	11m25s	0.38	0.15
6	11m53s	1.31	0.33
17	12m42s	2.00	0.70
7	14m09s	1.08	0.29
9	23m36s	1.10	0.30
10	24m01s	0.54	0.18
8	24m28s	0.94	0.27
11	27m08s	0.67	0.21
Total		31.63	

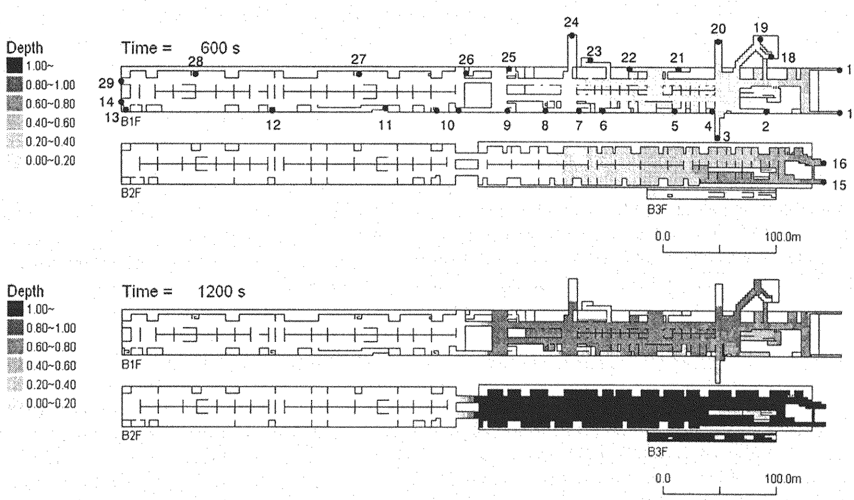

Fig. 5 Distributions of calculated water depth at t=600 seconds (upper) and t=1200 seconds (lower) from the beginning of inflow through the No.1 entrance.

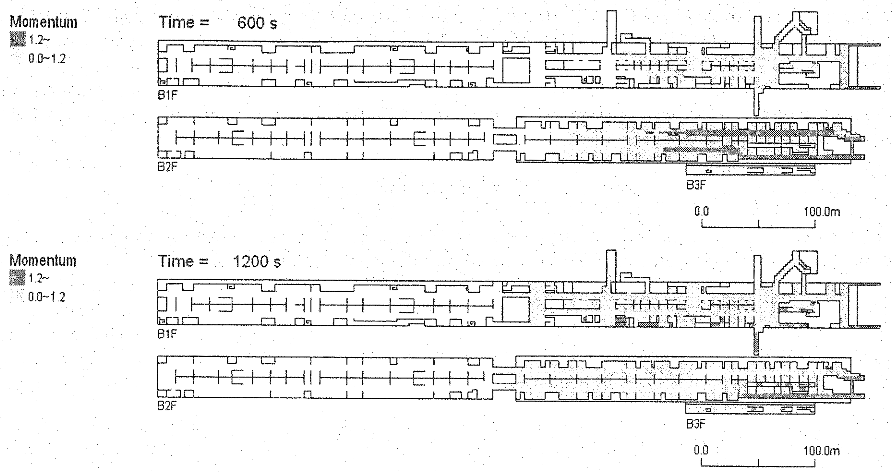

Fig. 6 Distributions of calculated momentum per unit width at t=600 seconds (upper) and t=1200 seconds (lower) from the beginning of inflow.

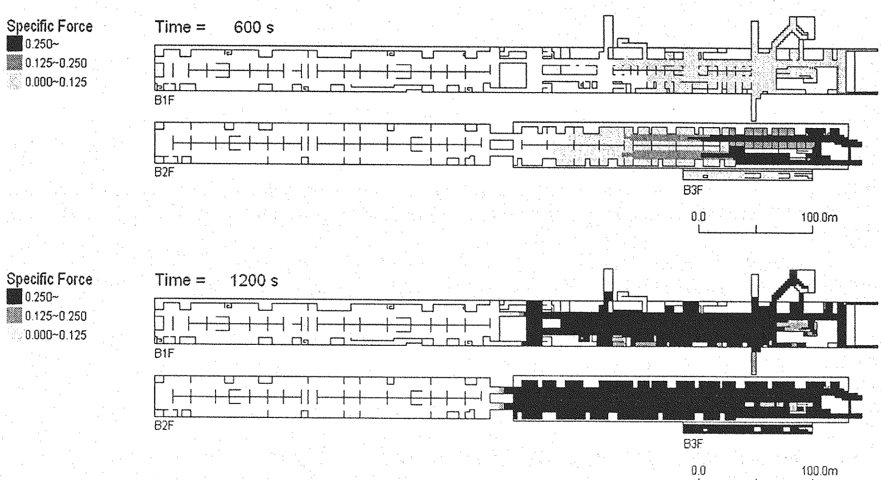

Fig. 7 Distributions of calculated specific force per unit width at t=600 seconds (upper) and t=1200 seconds (lower) from the beginning of inflow.

APPLICATION OF THE CRITERIA

Momentum and specific force are discussed above and the results show that the latter is better criterion for safe evacuation. These two criteria and water depth were tested here on the basis of simulation data by means of the 2D shallow flow model with 2m square meshes. An underground space located in Kyoto, Japan was selected as the area to be studied. Fig. 4 shows the structure of the underground space with a shopping arcade on the first basement, parking lots on the first and second basements and a subway platform on the third basement. The length is about 650m and the width is about 40m, and the subway platform is connected to the first basement.

As the underground space is adjacent to the Kamo river on the east side, this area is prone to inundation. Table 2 shows the inflow conditions through entrances on the ground into the space. These data were obtained in a previous study of hydraulic model tests (1). The entrance numbers are shown in Fig. 5. Such inflows are induced when the overflow discharge from the Kamo river is $100m^3/s$. This flood is equivalent to about 70 to 100 year flood.

Figs. 5, 6 and 7 show the distributions of water depth, momentum and specific force respectively at 600 and 1200 seconds. The inundation area spreads out from the first basement to the third basement. The subway platform on the third basement is very small, and then this area is quickly filled with water as shown in Fig. 5. Very small areas are indicated as difficult zones of safe evacuation in Fig. 6. In the underground space, the depth of inundated water is fairly deep as shown in Fig. 5, but its flow velocity is low. This is the reason why the value of momentum can not indicate the dangerous zones correctly. In contrast, the distributions of specific force per unit width show the dangerous zones appropriately as shown in Fig. 7. Calculated data are classified into three categories. The first category is in the range lower than 0.125 and safe evacuation was possible in this zone. The second category is in between 0.125 and 0.250. In this category, safe evacuation is difficult but possible with some difficulties. The third category is the range beyond the limit value of evacuation without any help. There is a possibility that people might come to a standstill in this situation. From the results, it was found that the specific force is able to show the difficulty and the extent of danger of an evacuation route correctly.

CONCLUSIONS

Criteria for safe evacuation has been investigated by means of evacuation test data and by using real size model of 20 steps stairs and 10m corridor, as well as simulation data of inundation by 2D shallow flow model. Findings of this study are summarized as follows; 1) specific force per unit width is a reasonable criterion for safe evacuation from inundated underground spaces, 2) $u^2h/g+h^2/2=0.125$ is the criterion for safe evacuation and 0.250 is the limit value of evacuation without any help for normal persons, 3) by using these criteria with a simulation method of inundation, safe evacuation routes could be determined and drawn up for a safe evacuation plan. As the criteria obtained in this work was for normal people. In the next step of this study, we need to investigate the values of those for the elderly, children and people with handicaps.

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APPENDIX – NOTATION

The following symbols are used in this paper:

- g =gravity acceleration;
- H =water depth on the ground;
- h =flow depth;
- t =calculation time;
- u =mean velocity;
- z =height of end plate.

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