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Critical rainfall intensity for safe evacuation from underground spaces with flood prevention measures[*]

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Abstract: Underground space in urban areas has been expanding rapidly during recent decades, and so has the incidence of fatal accidents and extensive damage to facilities resulting from underground flooding. To evaluate the safe evacuation potential of individual underground spaces in flood-prone urban areas, the hydraulic effects of flood prevention measures, e.g., stacked flashboards or sandbags and elevated steps, were incorporated in a proposed formula for estimating the depth of inundation of an underground floor. A mathematical expression of the critical rainfall intensity for safe evacuation from underground space was established and then evaluated for two types of underground spaces, an underground shopping mall and a building basement. The results show that the critical rainfall intensity for any individual underground space can be determined easily using the proposed analytical or graphical solution. However, traditional underground flood prevention measures cannot improve safety if people refuse to evacuate immediately once water intrudes into the underground space.

Key words: Underground space, Safe evacuation potential, Flood prevention measures, Critical rainfall intensity
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1 Introduction

Underground space in urban areas, created for the purposes of storage, shopping, recreation and even accommodation, has been increasingly and intensively exploited in recent decades (Takasaki *et al*., 2000; Wang *et al*., 2008; Bobylev, 2009; Evans *et al*., 2009). The utilization of underground space for urban infrastructure construction has been suggested as the main direction for sustainable development in China (Wang *et al*., 2008). However, underground space is also prone to flooding caused by rains, floods, failure of surface water structures, groundwater ingress, and leakage from underground water containers and conduits (Bobylev, 2007; 2009). This can lead to severe and unpredictable damage to underground facilities and can even threaten human lives (Greater London Authority, 2005; Teng *et al.*, 2006; Sander, 2007). For example, the 2002 flooding in Prague, Czech Republic, the 2001 torrential rains of the tropical storm ‘Allison’ in Houston, USA, the 2007 heavy rain in Jinan, China, the 1999 and 2003 floods in Fukuoka, Japan, and the 2005 flood in Tokyo, Japan caused huge damage to underground facilities. Several deaths resulted from the underground flood disasters reported in 1999 in Fukuoka and Tokyo, Japan (Kaneki, 2003; Toda, 2007) and 11 deaths in July, 2001 from the flood disasters in Seoul and Anyang, South Korea (CCIDUS, 2002).

When a large volume of rain or flood water flows into underground space within a short period of time, people in the underground space will be trapped and their lives will be threatened. Flood disaster prevention and mitigation measures, such as elevated entrances, flashboards, sandbags and drainage pumps, have been used to guarantee the safety of people and to mitigate the damage to underground facilities in building basements, underground car parks and shopping malls (Kawata *et al*., 2003; Bobylev, 2007;

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Pu, 2008). Kawata *et al*. (2003) reported that sandbags, flashboards and drainage pumps are the measures most commonly used against underground inundation disasters, based on the results of questionnaires and interview surveys in Japan. Bobylev (2007) reported that a feasible prevention measure for a relatively isolated underground space is to prevent water from entering by using engineering solutions such as hermetic doors, spatial design (drainage gutters, elevated entrances) and sandbags.

Even when flood prevention measures have been used to mitigate the risk of inundation, some risk to underground facilities still exists. A few studies have investigated this risk. Inoue *et al*. (2003) and Ishigaki *et al*. (2005) proposed an evacuation index (v^2h, where v is the flow velocity (m/s) and h is the water depth (m)) as a criterion to judge the ability of people to walk on stairways during experiments. To assess risk, Oertel and Schlenkhoff (2008a; 2008b) used the product number SN (=vh) (Abt *et al*., 1989; RESCDAM, 2000) for the entrance area of underground facilities and the critical drown depth (=1.5 m) for the underground floor area. In general, people can withstand an SN of 0.64–1.26 m^2/s when they walk on the ground (RESCDAM, 2000). The corresponding lower value of the overflow water depth at the entrance to a staircase to underground facilities is about 0.52 m (Oertel and Schlenkhoff, 2008a; 2008b), which is very close to the recommended value of 0.5 m for v^2h=1.5 m^3/s^2 proposed by Inoue *et al*. (2003). Ishigaki *et al*. (2005) tested the ability of people to walk on stairs by using real scale models of staircases. They concluded that an overflow water depth of no more than 0.3 m (v^2h=1.2 m^3/s^2) would be safer for people evacuating from an underground space via stairs. The corresponding inundation depth on an underground floor is usually less than the critical drown depth. Therefore, the ability to walk on stairs is the control condition for the safe evacuation of people from underground spaces.

In relation to the necessary evacuation time period, CCIDUS (2002) proposed a series of empirical formulas of evacuation intervals for a given underground space under a fixed rainfall intensity. That study also suggested that the critical overflow depth for the ability to walk on stairs is 0.3 m.

While the evacuation behavior of people and the use of flood prevention measures have been tested and formulas proposed, an evaluation of the critical flood level for safe evacuation, the most important issue for the administrators of underground space, has not yet been carried out. Therefore, this study focused on the determination of the critical rainfall intensity for the safe evacuation of people from a constructed underground space and the effectiveness of flood prevention measures. The results will be helpful to administrators in making decisions about when to evacuate and which measures to take to mitigate the damage and risks from flooding.

2 Determination of critical rainfall intensity for safe evacuation

2.1 Empirical formula for evacuation intervals from underground space

When a person is trying to evacuate from an underground space, the necessary evacuation time interval under a certain rainfall intensity from the farthest location in the underground space to the ground exit can be estimated by separating it into five stages (with the unit of s)(CCIDUS, 2002):
the danger recognition interval,

$$t_1 = \min(t_{1\mathrm{G}}, t_{1\mathrm{u}}); \tag{1}$$

the decision-making interval,

$$t_2 = 60(\sqrt{A_\mathrm{u}}/30 + 3); \tag{2}$$

the underground evacuation interval,

$$t_3 = \frac{60l}{v_\mathrm{u}(1 - h_\mathrm{u}/0.7)}; \tag{3}$$

the staircase entrance passing interval,

$$t_4 = 60\frac{pA_\mathrm{u}}{\sum N_\mathrm{eff} B_\mathrm{u}}; \tag{4}$$

and the evacuation interval on the staircase,

$$t_5 = \frac{60\lambda}{v_\mathrm{s}(1 - h_\mathrm{w}/0.3)}, \tag{5}$$

where $t_{1\mathrm{G}}$ is the time taken for the overflow depth to reach 10 cm (s); $t_{1\mathrm{u}}$ is the time taken for the depth of inundation water on the underground corridor floor to rise to 10 cm (s); A_u is the area of the underground floor (m^2); l is the distance from the farthest location in the underground space to the underground entrance of the staircase (m); v_u is the standard walking speed on the horizontal ground (m/min), v_u=60 m/min; h_u is the inundation depth on the underground floor (m); p is the people density (person/m^2) in the underground space; N_{eff} is the moving coefficient for people, N_{eff}=90; B_u is the width of the staircase entrance in the underground space (m); λ is the length of the staircase to the ground (m); v_s is the standard walking speed on the staircase (m/min), v_s=30 m/min; and h_w (m) is the overflow depth at the ground level entrance of the staircase (CCIDUS, 2002) (Fig. 1a) or the top of stacked flashboards or sandbags when flood prevention measures have been taken (Fig. 1b).

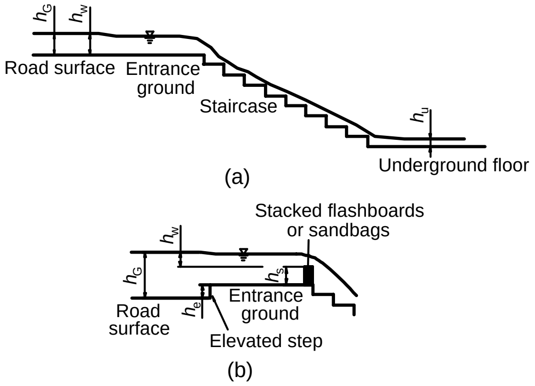


Fig. 1 Schematic of underground space and flood prevention measures under (a) normal situation and (b) situation with elevated step and stacked flashboards or sandbags

h_G is the inundation depth on the road surface (m); h_s is the height of the stacked flashboards or sandbags at the ground level entrance of the staircase (m); h_e is the height of the elevated step before the entrance to the underground space (m)

Thus, the time required to evacuate people from the farthest location underground to the ground exit will be the sum of t_1, t_2, t_3, t_4, and t_5.

2.2 Hydraulic effects of flood prevention measures on the underground inundation depth

Flooding of an underground space begins when rain water on the road surface overflows the ground level entrance and intrudes into the underground space. For a certain catchment area and inundation area around the entrance of an underground space, the evenly rising rate of increase in the depth of inundation water on the road surface can be determined (GB 50014-2006):

$$v_t = \frac{Ci_{\text{net}}A}{360A_G}, \tag{6}$$

where v_t is the evenly rising rate of increase in the depth of inundation water on the road surface (m/s); i_{net} is the net rainfall intensity producing runoff on the road surface (mm/h); C is the runoff coefficient known as an empirical value (GB 50014-2006); A_G is the inundated area around the entrance of the underground space (m^2); and A is the corresponding catchment area (10^4 m^2).

The overflow depth at the ground level entrance of the staircase (Fig. 1a) is

$$h_w = h_G = v_t t, \tag{7}$$

where h_G is the inundation depth on the road surface (m); and t is the time interval starting from the moment runoff starts on the road surface (s).

Once an elevated entrance and flashboards or sandbags are used, the overflow depth at the ground level entrance will differ from that in Eq. (7) (Fig. 1b) and become

$$h_w = h_G - h_s - h_e = v_t t - h_s - h_e, \tag{8}$$

where h_s is the height of the stacked flashboards or sandbags at the ground level entrance of the staircase (m); h_e is the height of the elevated step before the entrance to the underground space (m), which is always no more than 0.3 m (Ishikawa *et al*., 2002).

To determine the correlation curve between the intrusion discharge and the ground level entrance inundation depth through the staircase to the underground space, the National Institute for Land and Infrastructure Management (NILIM) of Japan proposed an empirical formula based on experimental tests, which was used in the Guidelines for Measures against Inundation of Underground Spaces (CCIDUS, 2002):

$$Q_u = aBh_w^b, \tag{9}$$

where Q_u is the discharge intruding into underground space through staircases (m^3/s); B is the sum of the entrance widths of flooding staircases (m); a and b are constants, a=1.590 and b=1.650 for CCIDUS (2002), or a=1.705 and b=1.500 by assuming the critical water depth has been reached at the ground level entrance, while Ishigaki *et al*. (2005) argued that a and b should be 1.980 and 1.621, respectively, based on experimental tests of real scale models of staircases.

Then, the volume V of rainwater intruding into an underground space through the stairs within a time duration of t_r is

$$\begin{aligned} V(t_\mathrm{r}) &= aB\int_{(h_\mathrm{s}+h_\mathrm{e})/v_t}^{t_\mathrm{r}} h_\mathrm{w}^b \,\mathrm{d}t \\ &= \frac{aB}{v_t(b+1)}(v_t t_\mathrm{r} - h_\mathrm{s} - h_\mathrm{e})^{b+1}, \\ &\quad \text{for } t_\mathrm{r} \geq (h_\mathrm{s}+h_\mathrm{e})/v_t. \end{aligned} \tag{10}$$

Considering the drainage pumping capacity in the underground space, the net volume V_u of inundation water on the underground floor is

$$\begin{aligned} V_\mathrm{u}(t_\mathrm{r}) &= \int_{(h_\mathrm{s}+h_\mathrm{e})/v_t}^{t_\mathrm{r}} (aBh_\mathrm{w}^b - Q_\mathrm{du})\,\mathrm{d}t \\ &= \frac{aB}{v_t(b+1)}\left(v_t t_\mathrm{r} - h_\mathrm{s} - h_\mathrm{e}\right)^{b+1} - Q_\mathrm{du}\left(t_\mathrm{r} - \frac{h_\mathrm{s}+h_\mathrm{e}}{v_t}\right), \\ &\quad \text{for } t_r \geq (h_\mathrm{s}+h_\mathrm{e})/v_t, \end{aligned} \tag{11}$$

where Q_du is the drainage pumping capacity in the underground space (m^3/s).

Taking the underground space as a storage pond, the inundation depth on the underground floor at time t_r is

$$\begin{aligned} h_\mathrm{u}(t_\mathrm{r}) &= \frac{a}{b+1}\frac{B}{A_\mathrm{u}v_t}(v_t t_\mathrm{r} - h_\mathrm{s} - h_\mathrm{e})^{b+1} \\ &\quad - \frac{Q_\mathrm{du}}{A_\mathrm{u}v_t}(v_t t_\mathrm{r} - h_\mathrm{s} - h_\mathrm{e}), \\ &\quad \text{for } t_\mathrm{r} \geq (h_\mathrm{s}+h_\mathrm{e})/v_t. \end{aligned} \tag{12}$$

Drainage pumping in underground space is an available means to lower the underground inundation depth as indicated in Eq. (12), which can shorten the underground evacuation interval t_3 according to Eq. (3). However, it cannot slow down the rate of increase in ground inundation depth at the ground level entrance of the staircase, which is the critical control condition for the safe evacuation of people from underground space. Therefore, the effect of underground drainage pumping was not considered in the following discussions, namely we have assumed $Q_\mathrm{du}=0$.

2.3 Mathematical expression of critical rainfall intensity for safe evacuation

Considering the effects of stacked flashboards or sandbags and elevated steps, the formula for the recognition of danger interval t_1 can be determined by combining Eqs. (1), (8) and (12):

$$t_1 = \begin{cases} \dfrac{h_\mathrm{d}+h_\mathrm{s}+h_\mathrm{e}}{v_t}, \quad \text{for } v_t > h_\mathrm{d}^b \dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}, \\ \dfrac{1}{v_t}\left[h_\mathrm{s} + h_\mathrm{e} + \left(h_\mathrm{d}\dfrac{b+1}{a}\dfrac{A_{\mathrm{u}0}v_t}{B}\right)^{\frac{1}{b+1}}\right], \\ \qquad \text{for } v_t < h_\mathrm{d}^b \dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}, \end{cases} \tag{13}$$

where $A_{\mathrm{u}0}$ is the area of the corridor of underground space (m^2); and h_d is the ground level entrance inundation depth or underground inundation depth for people beginning to evacuate (m). When h_d=0.1 m and $h_\mathrm{s}+h_\mathrm{e}$=0, Eq. (13) is the same as Eq. (1) as suggested by CCIDUS (2002).

After people in the underground space become aware that flooding is occurring and decide to act, the time is $t_\mathrm{r}=t_1+t_2$. Assuming the inundation depth on the underground floor when people start to run is the water depth at that moment, then h_u in Eq. (3) can be determined by Eqs. (12) and (13) as

$$h_\mathrm{u} = \begin{cases} \dfrac{a}{b+1}\dfrac{B}{A_\mathrm{u}v_t}\left[v_t t_2 + h_\mathrm{d}\right]^{b+1}, \\ \qquad \text{for } v_t > h_\mathrm{d}^b \dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}, \\ \dfrac{a}{b+1}\dfrac{B}{A_\mathrm{u}v_t}\left[v_t t_2 + \left(h_\mathrm{d}\dfrac{b+1}{a}\dfrac{A_{\mathrm{u}0}v_t}{B}\right)^{\frac{1}{b+1}}\right]^{b+1}, \\ \qquad \text{for } v_t < h_\mathrm{d}^b \dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}. \end{cases} \tag{14}$$

When people are trying to run up a staircase, the most dangerous situation occurs when $t=t_1+t_2+t_3+t_4$, which is the time taken for someone to arrive at the underground entrance of the staircase having come from the farthest location in the underground space. The overflow depth h_w in Eq. (5) will be

$$h_\mathrm{w}=\begin{cases} v_t(t_2+t_3+t_4)+h_\mathrm{d}, \text{ for } v_t>h_\mathrm{d}^b\dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}, \\ v_t(t_2+t_3+t_4)+\left(h_\mathrm{d}\dfrac{b+1}{a}\dfrac{A_{\mathrm{u}0}v_t}{B}\right)^{\frac{1}{b+1}}, \\ \qquad\qquad \text{for } v_t<h_\mathrm{d}^b\dfrac{a}{b+1}\dfrac{B}{A_{\mathrm{u}0}}. \end{cases} \tag{15}$$

For a certain underground space, the overflow depth h_w is the control condition for the maximum available evacuation time (CCIDUS, 2002; Inoue *et al*., 2003; Ishigaki *et at*., 2005). Assuming the critical overflow depth for the ability to walk on stairs is h_wc (m), then the maximum available evacuation duration T_c for safe evacuation from the underground space with the benefit of flood prevention measures is

$$T_\mathrm{c}=(h_\mathrm{wc}+h_\mathrm{s}+h_\mathrm{e})/v_t, \tag{16}$$

If people want to evacuate safely from the underground space, the necessary evacuation duration obtained by t_1, t_2, t_3, t_4 and t_5 should be shorter than this maximum available evacuation duration. Then, we have

$$t_2+t_3+t_4+t_5\le\frac{h_\mathrm{wc}-h_\mathrm{d}}{v_t}, \text{ for } v_t>h_\mathrm{d}^b\frac{a}{b+1}\frac{B}{A_{\mathrm{u}0}}. \tag{17}$$

$$t_2+t_3+t_4+t_5\le\frac{1}{v_t}\left[h_\mathrm{wc}-\left(h_\mathrm{d}\frac{b+1}{a}\frac{A_{\mathrm{u}0}v_t}{B}\right)^{\frac{1}{b+1}}\right], \tag{18}$$
$$\text{for } v_t<h_\mathrm{d}^b\frac{a}{b+1}\frac{B}{A_{\mathrm{u}0}}.$$

The only unknown item in Eqs. (17) and (18) is the rising rate of increase in the ground inundation depth. Therefore, the critical rising rate of increase in the ground inundation depth for people evacuating from the underground space safely, $v_{t,\mathrm{crit}}$, can be obtained by trial and error. The critical net rainfall intensity $i_\mathrm{net,crit}$ then can be obtained using Eq. (6):

$$i_\mathrm{net,crit}=\frac{360}{C}\frac{A_\mathrm{G}}{A}v_{t,\mathrm{crit}}, \tag{19}$$

Finally, the rainfall probability for safe evacaution can be determined based on an analysis of local rainfall series using a Pearson type III function.

We can also conclude from Eqs. (17) and (18) that whatever the height of stacked flashboards or sandbags, or elevated steps, the critical net rainfall intensity for safe evacuation for a given underground space will be the same, because $v_{t,\mathrm{crit}}$ determined by Eqs. (17) and (18) has nothing to do with the height of stacked flashboards or sandbags, or elevated steps.

3 Case studies and discussion

3.1 Case studies and scenarios

Two underground cases are discussed: one is a relatively large scale underground shopping mall in Hangzhou, China (Case 1), and the other is a small scale building basement from CCIDUS (2002) (Case 2). Their shapes and sizes are shown in Fig. 2 and Table 1. Three scenarios were studied:

1. Scenario 1 (S1): the normal situation with no flood prevention measures. t_1 is determined by Eq. (13) with h_d=0.1 m;
2. Scenario 2 (S2): the situation with $h_\mathrm{s}+h_\mathrm{e}$= 0.4 m, and people begin to evacuate at the exact time when water begins to intrude into the underground space, i.e., h_d=0 and $t_1=t_{1\mathrm{G}}=(h_\mathrm{s}+h_\mathrm{e})/v_t$;
3. Scenario 3 (S3): the situation with $h_\mathrm{s}+h_\mathrm{e}$=0.4 m, and where t_1 is determined by Eq. (13) with h_d=0.1 m.

In the following discussions, the critical overflow depth and the correlation curve of discharge and ground inundation depth suggested by Ishigaki *et al*. (2005) were employed, i.e., h_wc=0.3 m, a=1.980 and b=1.621.

3.2 Critical net rainfall intensity for safe evacuation by analytical solution

Assuming the value of the maximum time for safe evacuation from an underground space is T_c, the rate of rise in water depth can be determined by Eq. (17) or Eq. (18) and the evacuation intervals by Eqs. (1)–(5) through the method of trial and error (Table 2). The danger recognition interval t_1 for the building basement is determined by $t_{1\mathrm{u}}$ due to the small area of underground floor and faster rate of increase in underground inundation depth, while t_1 for the underground shopping mall is determined by $t_{1\mathrm{G}}$ due to its relatively large scale underground floor and fast rate of increase in ground inundation depth.

Considering the normal situation with no flood prevention measures (S1), once the net rainfall

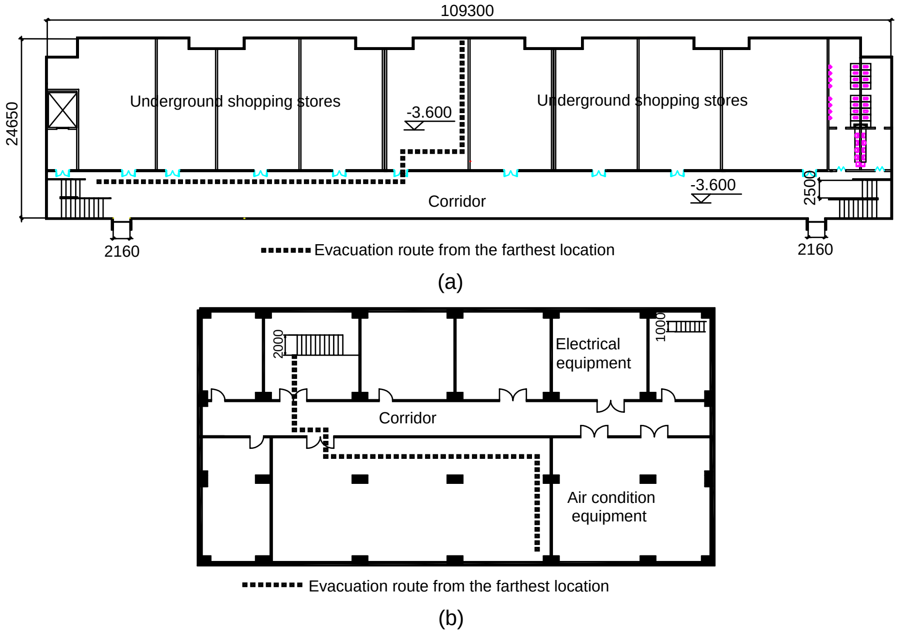


Fig. 2 Schematics of the studied underground spaces (unit: mm for sizes and m for elevations)
(a) Case 1: An underground shopping mall in Hangzhou, China; (b) Case 2: A building basement from CCIDUS (2002)

Table 1 Sizes of the studied underground spaces

Parameter	Case 1	Case 2
Width of No. 1 ground level entrance of staircase B_1 (m)	2.16*	1.00
Width of No. 2 ground level entrance of staircase B_2 (m)	2.16*	2.00
Area of underground floor A_u (m^2)	2661	455
Area of underground corridor floor A_{u0} (m^2)	655.8	82.0
Width of No. 1 underground entrance of staircase B_{u1} (m)	2.50	1.00
Width of No. 2 underground entrance of staircase B_{u2} (m)	2.50	2.00
Lengths of staircase λ_1, λ_2 (m)	7	10
Distance from the farthest location to underground entrance of staircase l (m)	70.00	23.20

* Controlled by the width of door

Table 2 Critical net rainfall intensity and evacuation time intervals for safe evacuation from underground space (analytical solution)

Parameter	Case 1			Case 2		
	S1	S2	S3	S1	S2	S3
t_1 (min)	6.09	15.60	30.44	3.04	9.04	16.68
t_2 (min)	4.72	4.72	4.72	3.70	3.70	3.70
t_3 (min)	1.25	1.19	1.25	0.49	0.42	0.49
t_4 (min)	4.14	4.14	4.14	1.15	1.15	1.15
t_5 (min)	2.06	1.65	2.06	1.85	1.50	1.85
T_c (min)	18.26	27.29	42.62	10.23	15.83	23.88
$v_{t,\text{crit}}$ (cm/min)	1.64	2.56	1.64	2.93	4.42	2.93
$i_{\text{net,max}}$ (mm/h)*	24.64	38.47	24.64	43.97	66.34	43.97
$(t_3+t_5)/T_c$	0.18	0.10	0.08	0.23	0.12	0.10

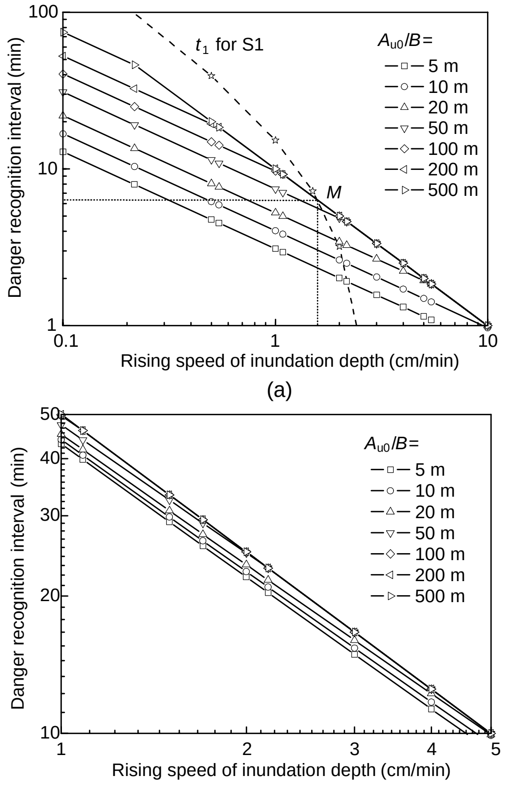
* The maximum net rainfall intensity is estimated by assuming C=0.8, A/A_G=50 m^2/m^2

intensity in this area is greater than the critical net rainfall intensity for safe evacuation, 43.97 and 24.64 mm/h, respectively, people in the basement and underground shopping mall will experience difficulty evacuating if there is no other evacuation route.

Table 2 shows that the recognition time interval t_1 and decision-making time interval t_2 are much longer than the actual evacuation time intervals of t_3 and t_5. The ratio of t_3+t_5 to T_c is about 0.18 to 0.23 for the normal situation of S1, and from 0.08 to 0.12 for the situation of S2 and S3 with flood prevention measures. Therefore, it is feasible to assume t_3+t_5 weights 20% of T_c for the normal case with no stacked flashboards or sandbags, or elevated steps, and 10% of T_c for the case with such flood protection measures used in the graphical solution.

3.3 Critical net rainfall intensity for safe evacuation by graphical solution

The danger recognition interval t_1 in Eq. (13) is a function of the rate of increase in ground inundation water depth v_t, the ratio of A_{u0}/B, and h_s+h_e (Fig. 3). The decision-making interval t_2 and the entrance-passing interval t_4 in Eqs. (3) and (5) are determined only by the sizes of the underground space and the widths of the staircases (Fig. 4).



(a)

(b)

Fig. 3 Danger recognition interval t_1 vs. the speed of the rise in ground inundation depth for (a) normal situation (h_s+h_e=0); (b) situation with h_s+h_e=0.4 m

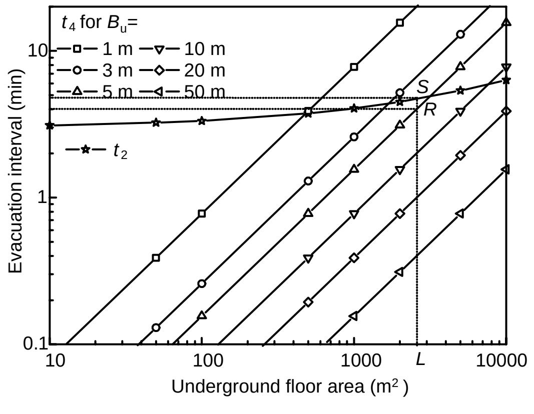


Fig. 4 The decision-making interval t_2 and the staircase entrance-passing interval t_4 (p=0.9 person/m^2)

Now we can obtain the critical rate of rise in inundation depth approximately by looking up in Figs. 3 and 4. Take the scenario S1 of the underground shopping mall as an example. First, determine the times of t_2 and t_4 by looking up in Fig. 4 based on the known value of A_u=2661 m^2 and B_u=5 m. Thus, we have t_2=4.7 min and t_4=4.1 min. Then, assume (t_3+t_5)/T_c=0.2 for the normal situation, and draw the curve of 0.8T_c−t_2−t_4, namely the curve of t_1 for S1 for the actual underground shopping mall as shown in Fig. 3a. Finally, find the crossing point of the curve of t_1 for S1 and one of the group curves of t_1 for A_{u0}/B=131.2 m, M, whose x-coordinate is the critical speed of the rise in ground inundation depth, about 1.6 cm/min, and y-coordinate value is the danger recognition interval, about t_1=6.2 min (Table 3).

Table 3 Critical net rainfall intensity and evacuation time intervals for safe evacuation from underground space (graphical solution)

Parameter	Case 1			Case 2		
	S1	S2	S3	S1	S2	S3
t_1 (min)	6.2	16.0	33.6	3.1	8.7	16.7
t_2 (min)	4.7	4.7	4.7	3.7	3.7	3.7
t_4 (min)	4.1	4.1	4.1	1.2	1.2	1.2
(t_3+ t_5)/T_c (assumed)	0.2	0.1	0.1	0.2	0.1	0.1
T_c (min)	18.8	27.6	47.1	10.0	15.1	24.0
$v_{t,\mathrm{crit}}$ (cm/min)	1.6	2.6	1.48	3.0	4.7	2.91
$i_{\mathrm{net,crit}}$ (mm/h)*	24.0	39.0	22.2	45.0	70.5	43.65

* The maximum net rainfall intensity is estimated by assuming C=0.8, A/A_G=50 m^2/m^2

The graphical solutions of the critical net rainfall intensity in the two cases are slightly different from those obtained by the analytical solution. The reason is that the assumption of the ratio of t_3+t_5 to T_c is slightly different. For example, t_3+t_5=0.20T_c for S1 has been used in the graphical solution of the basement while it is 0.23T_c in the analytical solution (Table 2).

3.4 Effects of the stacked flashboards or sandbags, and elevated entrance

Table 2 shows that the critical net rainfall intensities of S1 and S3 are the same even when stacked flashboards or sandbags, or elevated entrances are used at the ground level entrances of the underground space in scenario S3. The only difference between them is that the danger recognition interval of S3 is longer than that of S1 by the time interval (h_s+h_e)/v_t, namely the time taken for the ground inundation depth to rise to the height of the stacked flashboards or sandbags, or elevated entrances. It verifies the conclusion from Eqs. (17) and (18) that the height of stacked flashboards or sandbags, or elevated steps has no effect on the critical net rainfall intensity for safe evacuation from a given underground space. The stacked flashboards or sandbags, or elevated entrances cannot increase the rainfall intensity level for safe evacuation because people in the underground space are often too late to recognize the flood risk once these flood prevention measures have been implemented.

However, the critical net rainfall intensity for safe evacuation will be much greater if people in the underground space evacuate immediately once ground inundated water begins intruding into underground space as in scenario S2. People can evacuate safely even when the net rainfall intensity is up to 66.34 and 38.74 mm/h in scenario S2 because of the much shorter danger recognition interval (Table 2). However, the critical net rainfall intensity decreases quickly with increasing ground inundation depth h_d for people beginning to evacuate (Fig. 5). Therefore, to evacuate safely, people need to evacuate immediately once water begins to intrude into underground space even when mounted boards or sandbags, or elevated steps are used.

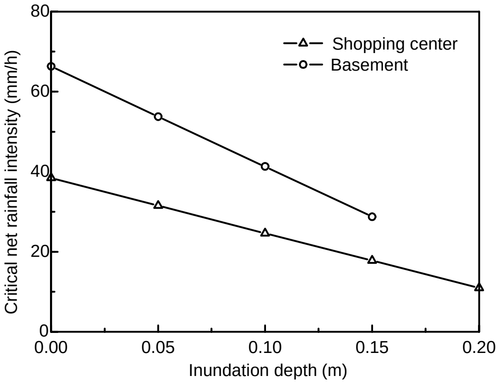


Fig. 5 The critical net rainfall intensity vs. the inundated depth h_d at the ground level entrance

If an elevated entrance is considered at the very beginning of the construction of an underground space, its effects on the evacuation will be the same as for stacked flashboards or sandbags discussed above. Whatever the height of an elevated entrance, the critical net rainfall intensity for safe evacuation from a certain underground space will be the same. The only difference is the prolonged time interval of danger recognition t_1.

In summary, both elevated entrances and stacked sandbags or flashboards are available and efficient measures for promoting safe evacuation. They can make sure that people have enough time to evacuate an underground space. Both elevated entrances and stacked sandbags or flashboards can keep water away from an underground space if located in areas prone to only shallow water inundation. However, if the conditions are suitable, elevated steps should have a higher priority than stacked sandbags or flashboards because of their convenience in requiring no extra work during rainfall events. In regions prone to deep inundation, the use of elevated steps can reduce the height of stacked flashboards or sandbags, enabling people to step over them more easily and without disrupting them. Stacked flashboards or sandbags can be used as a secondary measure in regions prone to deep inundation.

Watertight doors are similar to stacked flashboards or sandbags for keeping water away from underground space. However, the closure of watertight doors at inundated entrances will block evacuation exits if the underground space has no other exits for evacuation. Therefore, watertight doors at the ground level entrances of underground spaces are not a good choice for evacuation in regions prone to deep inundation if those ground level entrances are located on the way out.

4 Conclusions

The increasing occurrence of flooding disasters in urban areas makes various underground spaces such as basements, subway stations and shopping malls in flood prone areas more vulnerable to inundation. People and facilities in underground spaces are becoming exposed to increasing risks from flood inundation.

To cope with such urban underground flood disasters, structural and non-structural measures are being strongly promoted. Some administrators of underground spaces have installed flashboards or sandbags to prevent inundation. However, most of them do not know the critical intensity of rainfall at which the underground facilities will be at high risk of damage and people will not be able to evacuate from the underground space. For a certain underground space, the analytical and graphical solutions for the critical net rainfall intensity proposed in this paper can be used to solve this problem. For the design of an underground space, the methods can also be used to verify its safe evacuation potential by comparing the critical net rainfall intensity to the design rainfall intensity of the underground space.

Inundation mitigation measures used for underground spaces do not always work well. An elevated step before the entrance to an underground space could be an excellent structural measure in areas prone to shallow water inundation, preventing rain water from intruding into the underground space without any extra measures.

For areas prone to deep water inundation, elevated steps are not sufficient for inundation mitigation. Stacked flashboards or sandbags are a good choice for helping keep water out of underground spaces. The low height of stacked flashboards or sandbags can enable people to evacuate from underground space by stepping across the boards or sandbags safely.

Watertight doors are a good choice for those underground spaces with other evacuation routes or stairs in the building. However, if those exits with watertight doors are the exits needed for evacuation, the closure will block the evacuation route completely and trap the people in the underground space leading to a more serious situation. These circumstances may cause more panic and people will not be able to act calmly.

Drainage pumping in the underground space can be used to reduce the underground inundation water depth, but contributes little to safe evacuation.

References

Abt, S.R., Wittler, R.J., Taylor, A., Love, D.J., 1989. Human stability in a high flood hazard zone. *Water Research Bulletin, AWRA*, **25**(4):881-890.

Bobylev, N., 2007. Sustainability and Vulnerability Analysis of Critical Underground Infrastructure. *In*: Linkov, I., Wenning, R.J., Kiker, G.A. (Eds.), Managing Critical Infrastructure Risks: Decision Tools and Applications for Port Security, Springer, p.445-469. [doi:10.1007/978-1-4020-6385-5_26]

Bobylev, N., 2009. Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. *Land Use Policy*, **26**(4):1128-1137. [doi:10.1016/j.landusepol.2009.02.003]

CCIDUS (Committee of Countermeasures against Inundation Disasters in Underground Spaces), 2002. Guideline for Measures against Inundation of Underground Spaces. Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan (in Japanese).

Evans, D., Stephenson, M., Shaw, R., 2009. The present and future use of 'land' below ground. *Land Use Policy*, **26**(S1):302-316. [doi:10.1016/j.landusepol.2009.09.015]

GB 50014-2006. Shanghai Municipal Engineering Design General Institute (SMEDI). Code for Design of Outdoor Wastewater Engineering. National Standard of the People's Republic of China. China Planning Press, Beijing (in Chinese).

Greater London Authority, 2005. Climate Change and London's Transport Systems—Summary Report. Available from http://www.london.gov.uk/lccp/publications/transport.jsp [Accessed on Mar. 10, 2009].

Inoue, K., Toda, K., Nakai, T., Takemura, N., Oyagi, R., 2003. On the inundation process in the underground space. *Annuals of Disaster Prevention Research Institute, Kyoto University*, **46B**:263-273 (in Japanese).

Ishigaki, T., Toda, K., Baba, Y., Inoue, K., Nakagawa, H., Yoshida, Y., Tagawa, H., 2005. Experimental study on evacuation from underground space by using real size models. *Annuals of Disaster Prevention Research Institute, Kyoto University*, **48B**:639-646 (in Japanese).

Ishikawa, Y., Morikawa, H., Iida, M., 2002. Flood Forecasting and Management of Underground Spaces. *In*: Strecker, E.W., Huber, W.C. (Eds.), Global Solutions for Urban Drainage (CDROM). American Society of Civil Engineers. [doi:10.1061/40644(2002)269]

Kaneki, M., 2003. Minimization of Flood Disasters in Urban Areas. *In*: National Institute for Land and Infrastructure Management Ministry of Land, Infrastructure and Transport, Annual Report of NILIM, Tokyo, p.14-19.

Kawata, Y., Goto, R., Matsuo, I., 2003. A study on inundation disasters in the underground space in Japan and their countermeasures (1). *Annuals of Disaster Prevention Research Institute, Kyoto University*, **46B**:919-928 (in Japanese).

Oertel, M., Schlenkhoff, A., 2008a. Flooding of Underground Facilities in Urban Regions. 4th International Conference on Flood Defense, Toronto, Canada.

Oertel, M., Schlenkhoff, A., 2008b. Flood Wave Propagation and Flooding of Underground Facilities. River Flow, International Conference on Fluvial Hydraulics. Izmir, Turkey.

Pu, W.Q., 2008. Flood prevention and countermeasures for urban underground space. *Port & Waterway Engineering*, (10):223-228, 233 (in Chinese).

RESCDAM, 2000. The Use of Physical Models in Dam-break Flood Analysis. Research Report, Helsinki University of Technology, Finland.

Sander, E.G., 2007. Storm Report. Metropolitan Transportation Authority, London, UK.

Takasaki, H., Chikahisa, H., Yuasa, Y., 2000. Planning and mapping of subsurface space in Japan. *Tunnelling and Underground Space Technology*, **15**(3):287-301. [doi:10.1016/S0886-7798(00)00057-2]

Teng, W.H., Hsu, M.H., Wu, C.H., Chen, A.S., 2006. Impact of flood disasters on Taiwan in the last quarter century. *Natural Hazards*, **37**(1-2):191-207. [doi:10.1007/s11069-005-4667-7]

Toda, K., 2007. Urban flooding and measures. *Journal of Disaster Research*, **2**(3):143-144.

Wang, J.H., Koizumi, A., Liu, X., 2008. Advancing sustainable urban development in China. *Proceedings of the Institution of Civil Engineers: Municipal Engineer*, **161**(1):3-10. [doi:10.1680/muen.2008.161.1.3]