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EXPERIMENTAL STUDIES ON SAFETY EVACUATION FROM UNDERGROUND SPACES UNDER INUNDATED SITUATIONS

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Many cities in Japan are located in alluvial plains, and the vulnerability of urbanized areas to flood disaster is highlighted by frequent flooding due to heavy rainfall or typhoon. Underground spaces are also flood-prone areas because those are below the ground, and water intrusion into underground space inflicts severe damages on human beings and urban functions and infrastructures.

In order to reduce human suffering due to flood inundation in underground spaces and low-lying areas, needless to say, early evacuation is one of the most important countermeasures. This paper shows some experimental results of evacuation tests from underground spaces under inundated situations.

The difficulties of evacuation from underground space was investigated by using three real-scale models (door, staircase, and car), and the limits for safety evacuation is discussed. From the results, it is found that water depth of 0.3–0.4m would be a critical condition for safety evacuation through staircase and door while 0.7–0.8m deep on the ground would be a critical situation for safety evacuation through the doors of the car. The relationship between the critical depth condition for the safety evacuation and the age of male subjects was also investigated by using the experimental results of real-scale door model tests and the Physical Fitness Survey results.

A multiple regression model presented here properly reproduces the characteristics of the experimental results, such as the critical depth condition and its age-associated difference for safety evacuation. The same model is applied to the female's experimental results of real-scale door model tests and shows the overall distribution of the experimental results although the regression output still has considerable variation, especially in the young generation.

Key Words : *urban flood, underground space, evacuation tests, real-scale models*

1. INTRODUCTION

Torrential rains have been observed frequently in recent years in Japan, and the rainfalls over the capacity of drainage system have grown in frequency. These severe rainfalls cause inundations in many places in Japan.

Most urbanized areas developed in alluvial plains have underground spaces, and underground spaces have important roles in enhancing city functions (like subways, motorways, shopping malls, and parking lots) in the heavily built-up urbanized areas. Meanwhile, the underground spaces are prone to flood events.

Underground motorways (including underpasses) are also flood-prone areas. Some accidents involving submerged cars often occur around low-lying areas with "bowl-shaped" depression due to the heavy downpour within a short duration.

Once flood events happen in the urban area, water intrusion occurs in the underground spaces, and infrastructures and cumulated properties are damaged severely. In the worst-case scenario, unfortunately human sufferings are caused by underground inundations. Against the backdrop of these heightened concerns, some research activities on urban flooding

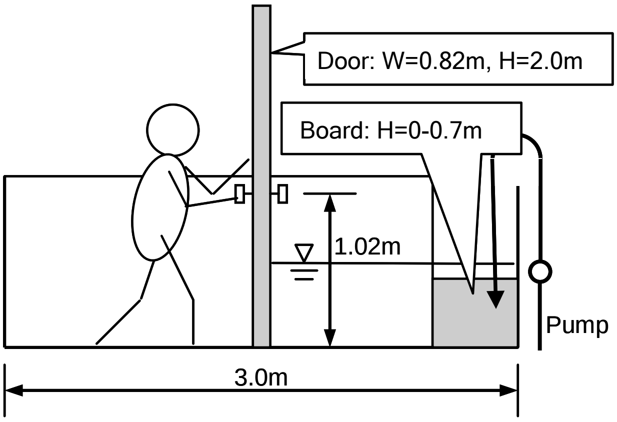


Fig.1 Real-scale model of door.

Photo 1 Participatory test with door model.

have been carried out[1), 2), 3), 4), 5), 6)].

In order to reduce the human damage caused by the inundation in underground spaces, needless to say, evacuation behavior at the early stage is one of the effective and important countermeasures. The objectives of this study are to summarize and to discuss the difficulty of safety evacuation based on the experiment results by using real-scale models. Furthermore, investigations on the difficulty of safety evacuation were also performed considering personal characteristics such as gender and age. In this study, an attempt to illustrate a connection between the subjects' age and the water depth conditions for the safety evacuation was made. It would be easy to imagine the existence of the relationship between the subjects' age and the water depth conditions for the safety evacuation; however, clarifying the relationship and its background was not easy. A multiple regression model with Physical Fitness Survey results was employed to investigate the relationship between the subjects' age and the results of the participatory model tests.

2. EXPERIMENTS WITH REAL-SCALE MODELS

In some past cases of urban flooding, inundation in underground space often happened which, unfortunately, caused human sufferings. In order to reduce the human suffering under inundated situations, it is pointed out that detailed investigations on the difficulty and limitation for safety evacuation are required[7), 8), 9), 10), 11), 12), 13)].

In the case of evacuation under inundated situations, evacuation behaviors are divided roughly into two patterns as follows:

a. opening the door and getting out from a space (room or car)
b. moving to a safe place through the corridor or staircase

Three real-scale models of door, staircase, and car were employed to investigate experimentally the difficulty and limitation of safety evacuation. In the following sections, some experimental results with these models are shown and discussed (Engineering unit system is often used in the following sections to facilitate the comparisons of the experimental data and body weight). The critical depth condition in this paper means "water depth condition that would cause a difficult situation for safety evacuation", and the evacuation rate means the ratio of the number of subjects who can evacuate to the number of all subjects.

(1) Evacuation tests through a door

a) Real-scale door model

To investigate the critical depth condition in front of a door for safety evacuation, a real-scale model of door was made, and some participatory experiments was conducted. **Fig.1** shows the experimental setup of the door model. The model has a door (0.82m wide) sandwiched by two tanks, and subjects can try to push or pull the door open. Fifty-six subjects (44 males and 12 females) had real-scale model tests to open the door with several experimental conditions.

Human power to open the door in the upright position was also measured by using a load scale for each subject.

b) Participatory tests of evacuation with door model

Fig.2 shows the relation between pushing force by subjects and their weights. It is found that the measuring results of pushing force are in between 45 and 80% of their own weight for male subjects. In the females' case, the results would be in between 40% and approximately 70% of their own weight. If the normal weight is 65 kilograms for men, the maximum expected pushing power is about 52 kilograms

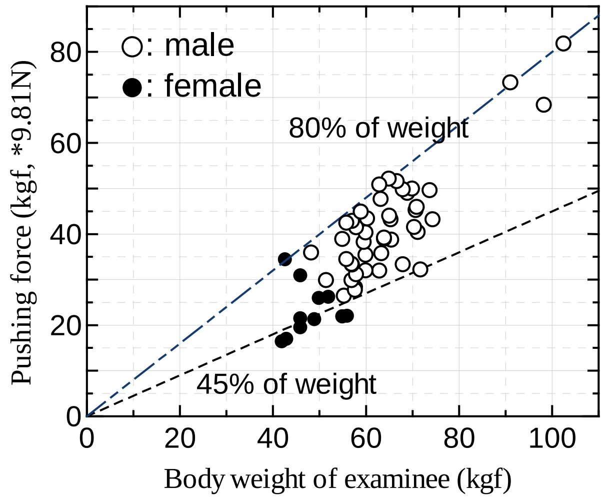


Fig.2 Relation between pushing force of subjects and their body weight.

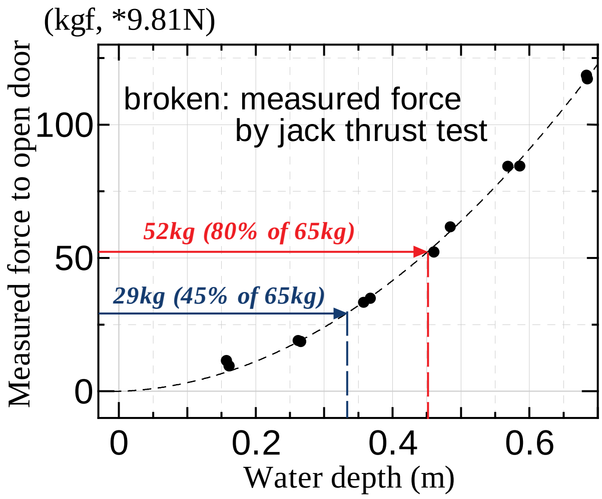


Fig.3 Measured results of water pressure and required pushing force to open the door[8].

(80% of the body weight) and the minimum expected pushing power about 29 kilograms (45% of the body weight) by using the results.

The broken line in **Fig.3** illustrates the relationship between the required pushing force to open the door and water depth in front of the door[8]. Required pushing force to open the door is measured by jack thrust test with a load cell. Based on the relationship, the critical depth condition is estimated by the expected pushing force mentioned above. The critical depth condition for male subjects is estimated between about 0.33m (corresponding to pushing force of 29 kilograms) and about 0.45m (corresponding to pushing force of 52 kilograms) shown in **Fig.3**. This result indicates that the water depth of around 0.4m would be the critical depth conditions for safety evacuation for male subjects.

The followings are the distribution of the critical depth condition for male subjects (the number of available data is 38).

0.3m - 0.4m: 0% (0 subject)
0.4m - 0.5m: 89.5% (34 subjects)
0.5m - 0.6m: 10.5% (4 subjects)

This distribution means that all subjects are able to open the door in the case of under 0.4m deep and the evacuation rate rapidly decreases in the case of more than 0.4m deep. In other words, for most male subjects, water depth of around 0.4m deep would be the critical condition for the safety evacuation, and this result supports the estimated critical depth condition derived by the relationship between body weight and pushing force.

In the same way, the critical depth condition for female subjects is also estimated by using the relationship in **Fig.2** and **Fig.3**. If the normal weight is 50 kilograms for women, the maximum expected pushing power is about 35 kilograms (70% of the body weight) and the minimum expected pushing power about 20 kilograms (40% of the body weight) by using the results in **Fig.2**. In **Fig.3**, the critical depth condition for female subjects is estimated between about 0.29m (corresponding to pushing force of 20 kilograms) and about 0.37m (corresponding to pushing force of 35 kilograms). This result indicates that the water depth of around 0.3m would be the critical conditions for safety evacuation for female subjects.

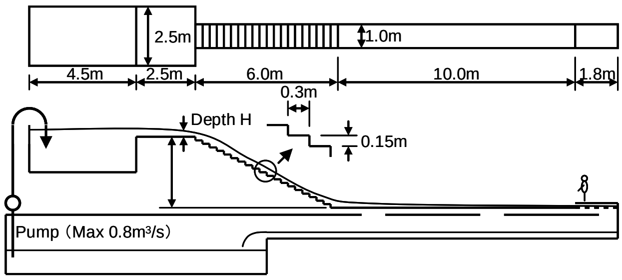


Fig.4 Real-scale model of staircase.

(2) Evacuation tests through staircase

a) Real-scale staircase model

To simulate the intrusion of flood water over a staircase, a real-scale model of staircase was installed as shown in **Fig.4**. There are 20 steps of which tread is 0.3m and riser is 0.15m. The sizes of both tread and riser are standard and are used typically for staircases in public spaces in Japan. The total height of the staircase is 3m and the width is 1m. Maximum flow discharge is up to $0.8m^3/s$, and the water depth on the ground level H is variable (maximum H is 0.5m).

b) Participatory tests of evacuation with staircase model

The number of subjects of the evacuation test was

Photo 2 Participatory test with staircase model.

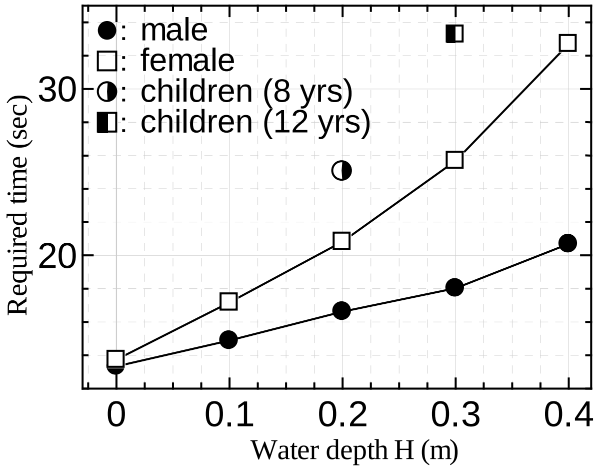


Fig.5 Comparisons of required time for evacuation.

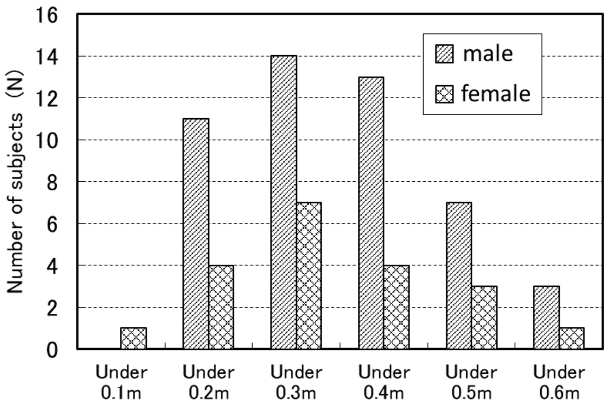


Fig.6 Questionnaire results on the water depth limit for safety evacuation through staircase.

more than 100, including 11 children of 8 years and 3 children of 12 years. Required time for evacuation was measured under four experimental conditions (H=0.1, 0.2, 0.3, and 0.4m). Here, "Required time" is the summation of the time for walking in the corridor (5m long) and staircase (20 steps).

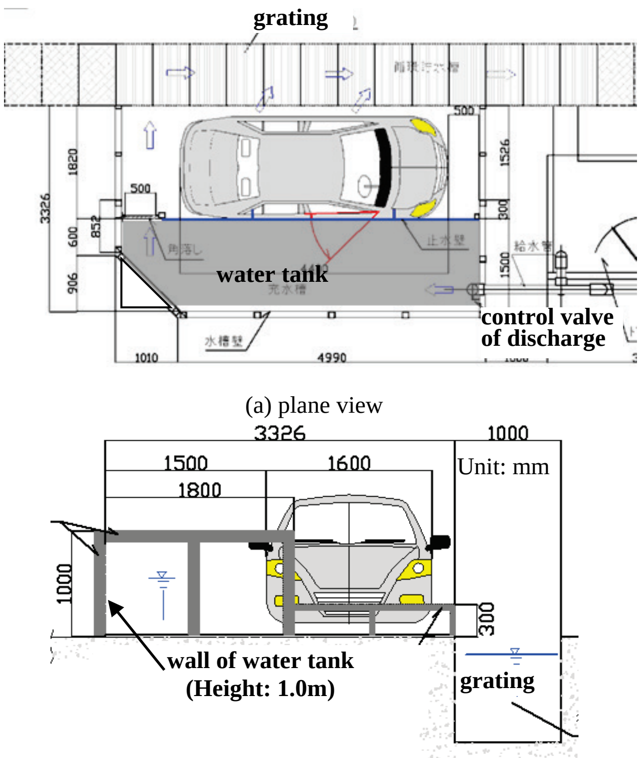
The comparisons of required time for evacuation are shown in **Fig.5**. The required time for evacuation becomes longer with an increase in the depth conditions in both male and female cases. The rate of increase of the required time for evacuation is bigger in the case of females than that in males. The required time for evacuation in the case of children is considerably bigger than the one in adults, and this result indicates that the critical depth condition for the safety evacuation would be lower than thought although the number of children subjects is not sufficient for discussion.

Fig.6 shows the results of a questionnaire survey among subjects asking about the water depth limit for safety evacuation after the evacuation test. Many subjects recognized the water depth of 0.3m on the ground as the depth limit. Moreover, it is easily expected that the critical depth conditions for children and the elderly would be shallower than the critical depth condition above.

(3) Evacuation tests through the door of a submerged car

a) Real-scale car model

The experimental setup is shown in **Fig.7**. A car in the sedan category is used for the model, and the car is fixed on the floor. The model consists of the car, water tank, and pumping system. The water tank is located in the driver side, and water depth in the tank is variable from 0 to 1m (The bottom of the door is 0.32m high above the floor).



(a) plane view

(b) cross-section view

Fig.7 Real-scale model of car (sedan car).

In order to investigate the required pushing force to open both front and rear doors, measurements of pushing force were carried out by jack thrust test with a load cell. **Fig.8** illustrates the required pushing force to open the front and rear doors. The broken lines represent fitted curves of the second order. Measured results rise rapidly according to the increase in water depth, and the required pushing forces to open the rear door is equal to almost 60%–70% of the one to open the front door. The difference in the required force between front and rear door results from the difference in the shape of the door.

b) Participatory tests of evacuation with car model

Fig.9 shows the variations in evacuation rates and averaged evacuation time to water depth above the door bottom in the cases of front and rear doors (the number of subjects is 45). In the case of the front door, as water depth rises, longer evacuation time is needed and the possibility of evacuation suddenly decreases if water depth above the door bottom exceeds 0.4–0.45m deep (around 0.7–0.8m deep above the floor). In the case of the rear door, the experimental results show similar characteristics; however, the increase rate of evacuation time is relatively small and the evacuation rate maintains a high level.

Another series of participatory tests was conducted in the case of evacuation through a sliding door. The experimental setup for the experiments involving sliding door (**Photo 4**) is much the same as the one in **Fig.7**. The only difference is the type of the car, and the use of a mini-vehicle with a sliding door. The bottom of the door is 0.31m high above the floor in this case. The experimental results with the mini-vehicle are shown in **Fig.10**. The experimental results are similar to the one of the sedan case. Also, the evacuation behavior through the sliding door is more difficult than the one through the front door (single swinging door). The water depth more than 0.4m (more than 0.7m deep above the floor) is a nearly critical condition for the safety evacuation because the evacuation rate rapidly decreases.

There is a big difference in the method of opening a single swinging door and a sliding door. In the case of a single swinging door, an evacuee pushes the single swinging door outward against the water pressure to the door. In this case, the pushing direction by an evacuee is opposite to the one of water pressure to the door.

In the case of a sliding door, an evacuee needs to combine the following actions to open the door: one is pushing the door outward and the other is drawing the door backward. The subjects commented after the participatory tests that the combined movement

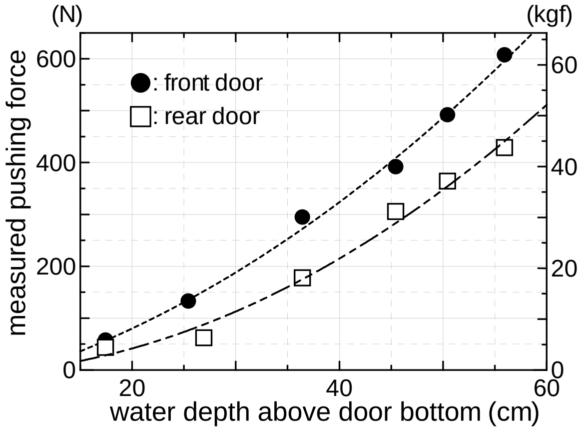


Fig.8 Required forces to open the front and rear doors.

Photo 3 Participatory test with car model.

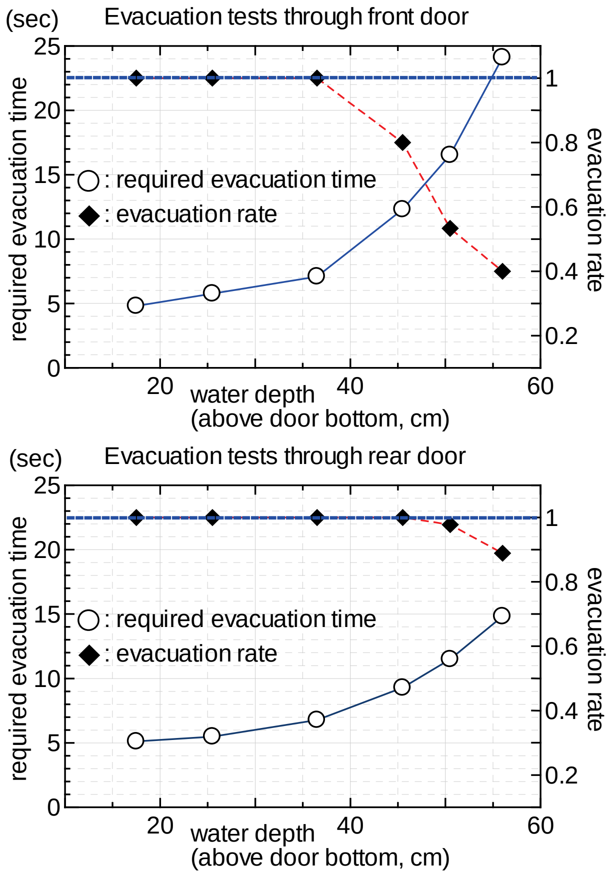


Fig.9 Evacuation time and evacuation rate through the front (top) and rear (bottom) doors (sedan car).

Photo 4 Experimental setup of car model (mini-vehicle).

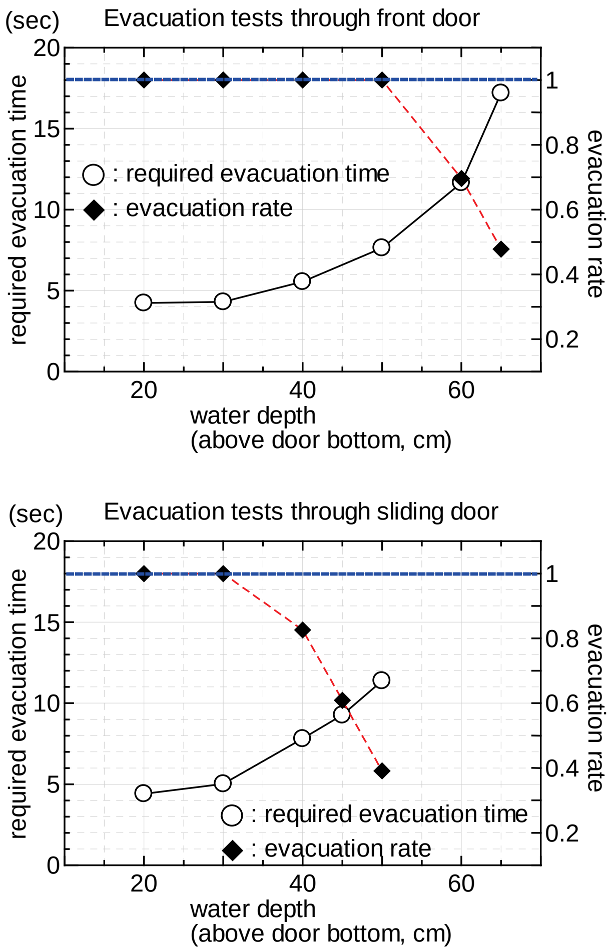


Fig.10 Evacuation time and evacuation rate through the front (top) and sliding (bottom) doors (mini-vehicle).

to open the sliding door mentioned above was rather troublesome, especially under deeper water condition. Thus, it is considered that the difference in the method of opening doors would be one of the reasons why the evacuation behavior through the sliding door would not be easy.

3. RELATIONSHIP BETWEEN THE EXPERIMENTAL RESULTS AND THE SUBJECTS' AGE

In the previous chapter, the comprehensive results of the critical conditions for the safety evacuation under inundated situation were derived based on the participatory evacuation tests by using the real-scale models.

However, the experimental results in the previous chapter included a considerable variation due to individual differences. Generally, physical capabilities vary with age, including the influence of individual differences and a difference in gender.

It is therefore deemed that the critical depth conditions for the safety evacuation would vary to a certain degree according to the physical capabilities and the gender of the subjects. In this chapter, the relationship between the critical depth conditions for the safety evacuation and the subjects' age is discussed based on the participatory test results in the use of a door model by male subjects.

(1) Results of the Physical Fitness Survey (Japan Fitness Test)

In Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) has been conducting Physical Fitness Surveys since 1964. The Physical Fitness Survey has several investigation items related to physical capabilities, and the investigated results are grouped into 26 classes according to age. The investigation items of the Physical Fitness Survey consist of nine physical tests related to muscle strength, muscle endurance, bendability, agility and general endurance.

In this research, the investigation items related to muscle strength, namely grip strength, sit-ups and standing long jump, were chosen as parameters to explain the individual differences in physical capabilities because muscle strength was considered to be closely related with physical strength, such as pushing power. The results of grip strength and sit-ups in the 26 age classes and standing long jump in the 23 age classes are shown in **Table 1**[14].

(2) Distribution of the experimental results in the use of the door model by male subjects

The evacuation test in the use of the door model by male subjects had the most number of participants among all evacuation tests mentioned in the previous chapter, and the number of available data was up to 397. The 397 experimental results were grouped into 26 age-based classes according to the results of the Physical Fitness Survey, and the averaged experi-

Table 1 Physical Fitness Survey results, averaged experimental results and estimated critical depth conditions (male subjects)[14)].

age (years)	weight (kg)	grip strength (kg)	sit-ups (times)	standing long jump (cm)	averaged experimental results (cm)	estimated water depth (cm)
6	21.15	9.39	11.50	113.97		20.75
7	23.80	11.14	14.15	125.55		23.03
8	26.58	12.80	15.96	137.92	28.33	25.15
9	30.33	14.63	17.83	145.62		27.12
10	33.72	16.92	20.28	156.50		28.94
11	37.90	19.84	22.29	165.13	28.00	30.61
12	43.28	24.71	24.48	181.99	30.50	32.15
13	49.25	30.62	27.79	199.27	33.85	33.56
14	53.96	35.66	29.89	213.85		34.84
15	58.28	38.57	29.38	216.96	33.66	36.01
16	60.50	41.31	30.94	224.73	36.36	37.06
17	61.93	42.82	32.14	229.27	34.74	38.00
18	62.41	42.80	30.16	226.95	45.00	38.85
19	62.70	43.72	30.92	230.59	40.59	39.59
20-24	65.63	46.82	28.78	225.66	40.27	41.50
25-29	66.79	47.47	27.42	222.86	45.00	42.66
30-34	67.93	47.64	25.21	216.38	44.00	42.45
35-39	69.34	47.70	24.14	210.57	41.11	41.34
40-44	69.77	47.92	23.44	206.70	34.55	39.69
45-49	69.55	47.53	22.64	200.73	40.00	37.82
50-54	68.63	46.25	21.24	193.60	34.00	35.96
55-59	67.28	44.82	19.36	186.56	37.50	34.28
60-64	65.27	42.52	17.71	176.20	33.57	32.85
65-69	63.94	39.54	14.51		30.00	
70-74	61.80	37.49	12.89			
75-79	60.74	34.71	11.10		30.00	

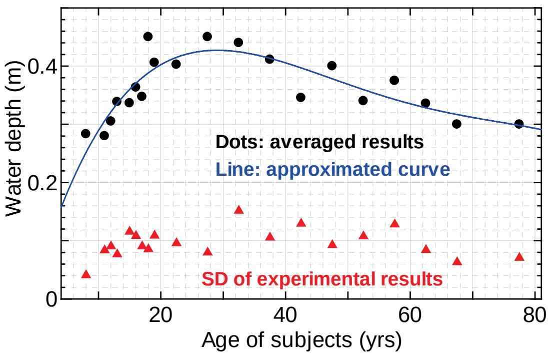


Fig.11 Experimental results of evacuation test with door model.

mental data with more than five subjects are shown in **Table 1**.

Fig.11 illustrates the distributions of the averaged experimental results, standard deviation of the experimental data, and the approximate quartic curve of the averaged experimental results. The details of the approximate quartic curve are as follows:

$$\begin{aligned} \text{depth (m)} = {} & 3.332\times10^{2} \\ & + 3.487\times10^{2}\times\text{Age} \\ & + -1.042\times10^{-3}\times\text{Age}^{2} \\ & + \ 1.206\times10^{-5}\times\text{Age}^{3} \\ & + -4.971\times10^{-8}\times\text{Age}^{4} \end{aligned} \quad (1)$$

determination coefficient: 8.724×10^{-1}

The averaged experimental data have wide distribution due to insufficient number of participants. However, the maximum depth condition is around 0.4m deep between the ages of 20 and 40, and this result corresponds to the critical depth condition of door model test presented in the previous chapter.

The distribution of the averaged experimental data shows realistic characteristics as follows: (1) the peak of the distribution is around 0.4m deep between the ages of 20 and 40, (2) the critical depth conditions for the elderly and children are relatively low, and (3) the critical depth conditions in the young generation increase according to the improvement of physical ability.

In the following data analysis, the approximate quartic curve of the averaged experimental data is used as the distribution of the critical depth conditions for male subjects, and the estimated values of the depth condition of 23 age-based classes by the quartic curve are shown in **Table 1**.

(3) Multiple regression model

In order to estimate the calculated distribution of the critical depth condition in the column of "estimated water depth" in **Table 1**, a multiple regression

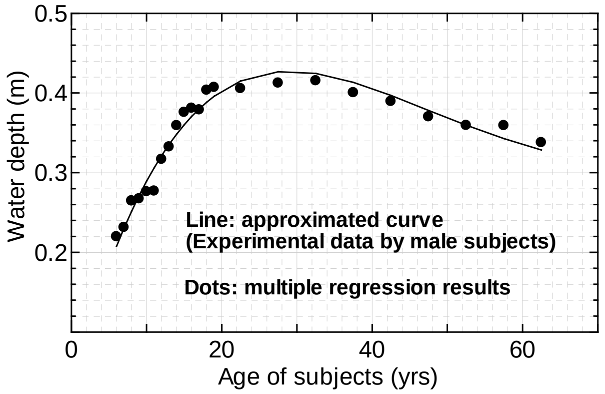


Fig.12 Comparison between the calculated results and experimental results.

model was adopted. The investigated results of body weight, grip strength, sit-ups, and standing long jump were used as input data for the multiple regression model.

Before the multiple regression analysis, all input data and the estimated data (the calculated depth condition) were standardized for each item. A statistical software "R (ver 3.2.3)" was used, and the multiple regression analysis was performed by using command "*lm*".

Initially four input data (weight, grip strength, sit-ups, and standing long jump) were used for the multiple regression analysis. After the variable selection, the data combination of grip strength, sit-ups, and standing long jump were found to produce better estimated results. The obtained multiple regression model is as follows (all data are standardized value):

$$\begin{aligned} \text{depth} = & -3.980\times10^{-16} \\ & + -9.672\times10^{-1}\times a_1 \quad (0.0301)^{*} \\ & + -1.862\times a_2 \quad (0.0020)^{**} \\ & + 3.509\times a_3 \quad (0.0005)^{***} \end{aligned} \qquad (2)$$

a_1: grip strength, a_2: sit-ups, a_3: standing long jump
( ) denote P value for regression coefficients

Fig.12 shows the comparison between the critical depth condition in the column of “estimated water depth” in **Table 1** and the estimated results by the multiple regression model. The estimated results by the multiple regression model have good agreement with the overall trend of the calculated distribution of the critical depth condition in **Table 1** even though the estimated maximum value is a little smaller than the calculated results, and the estimated results in the young generation have relatively large variability.

(4) Application of the regression model to the experimental results of the door model by female subjects

The number of the available data of the experimental results of using the door model by female subjects is 132 and is not insufficient in order to estimate the critical depth conditions according to age in the same way mentioned above.

Table 2 Physical Fitness Survey results (female subjects)[14].

age (years)	weight (kg)	grip strength (kg)	sit-ups (times)	standing long jump (cm)
6	20.73	8.79	10.95	106.37
7	23.37	10.34	13.73	119.42
8	26.39	12.12	15.25	129.42
9	29.84	14.02	16.75	138.30
10	34.00	16.28	18.36	146.77
11	38.73	19.27	20.21	155.64
12	43.49	22.06	20.51	164.25
13	46.71	24.42	23.52	171.74
14	49.36	25.63	24.23	173.90
15	51.15	25.64	22.18	168.33
16	51.80	26.55	23.18	169.77
17	52.64	27.03	23.90	170.58
18	51.68	26.66	22.66	169.35
19	51.72	26.52	22.86	169.76
20-24	50.76	28.38	20.80	166.55
25-29	51.15	28.57	18.93	163.05
30-34	51.07	28.94	17.19	159.76
35-39	51.37	29.19	16.77	157.94
40-44	52.36	29.68	16.58	155.50
45-49	52.89	29.14	15.87	151.95
50-54	53.16	28.32	14.78	146.81
55-59	53.09	27.08	12.22	137.89
60-64	52.69	26.21	10.99	129.15

The multiple regression model based on the experimental results among male subjects is derived by using several results of the Physical Fitness Survey. In other words, it is possible to say that this multiple regression model explains part of the relationship between several results of the Physical Fitness Survey and the experimental results on the critical depth condition for safety evacuation. The multiple regression model is also applicable to estimate the critical depth conditions according to age in the female case without any model modification.

The investigated results of grip strength, sit-ups, and standing long jump among female subjects are shown in **Table 2**[14]. These investigated results are also covered by the same standard derived by the investigated results among male subjects in **Table 1**.

Fig.13 shows the comparison between the critical depth condition in the column of “estimated water depth” in **Table 1** and the estimated results by using the multiple regression model with the investigated results of female subjects of Physical Fitness Survey. The estimated results in **Fig.13** have relatively large variability in the young generation as those shown in

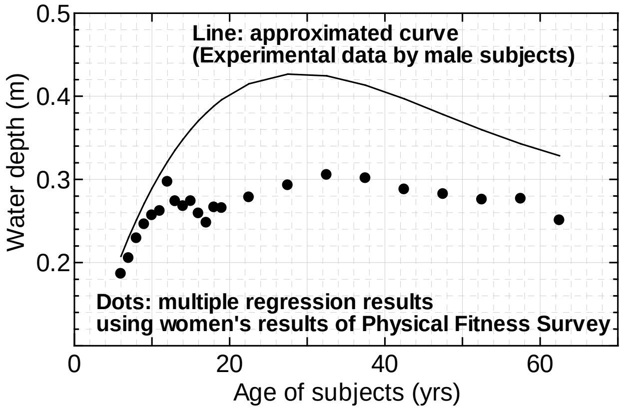


Fig.13 Comparison between the calculated results and experimental results.

Fig.12. However, the maximum peak of the distribution is around 0.3m deep. This means that the estimated results by the multiple regression model have agreement with the experimental results in the previous chapter.

4. DISCUSSION

In the previous chapters, the critical depth conditions for the safety evacuation under the inundated situations are discussed with the experimental results of a series of the participatory tests of evacuation with three real-scale models of door, staircase and car. The critical conditions for safety evacuation in the cases of door, staircase, and car are roughly estimated based on the experimental results. The estimated critical conditions would be nearly equal to the maximum depth conditions for safety evacuation and must provide a guideline to address the safety under inundated situations, although the obtained results by the participatory tests are still uncertain due to inadequate number of the subjects.

The relationship between the critical depth conditions and the subjects' age is discussed based on the participatory test results of the door model by male subjects. The relationship between the critical depth conditions and the male subjects' age is well reproduced by the multiple regression model with several investigated results of the Physical Fitness Survey. This result indicates a possible connection between the experimental results of real-scale models and the Physical Fitness Survey results.

The experimental results presented here still bear uncertainty because of the inadequate number of subjects, and more accumulation of data is required in order to obtain more accurate relationship between the experimental results of real-scale models and the Physical Fitness Survey results.

Despite the uncertainty due to insufficient data, the multiple regression model using the Physical Fitness Survey results can be used to estimate critical depth condition in the case of paucity of available data. In **Fig.13**, the estimated distribution of the critical depth condition for female subjects is shown, and the estimated results by the multiple regression model have characteristics that correspond to the experimental results.

The estimated results by the multiple regression model have relatively large variability especially in the young generation as shown in **Fig.13**. The young generation is a period of rapid physical growth, and physical performance develops with age as shown in **Table 1** and **Table 2**. As a result, it is expected that the critical depth conditions for safety evacuation would have a monotonic increasing trend in the young generation like the approximate curve in **Fig.13**. However, the distribution of the estimated results in **Fig.13** does not show a monotonic increasing trend in the young generation. In order to improve the estimation of the critical depth conditions in the young generation, other parameters or another model may be required based on the adequate experimental data.

5. CONCLUDING REMARKS

This paper shows some experimental results of evacuation tests from underground spaces by using three real-scale models of door, staircase, and car, and the relationship between the experimental results of the door model and the subjects' age is also discussed. The main results obtained are as follows:

(1) The experimental data are summarized to obtain the critical depth conditions for safety evacuation under inundated situations. The experimental results show that a water depth of 0.3–0.4m would be a critical situation for the safety evacuation through staircases and doors and that 0.7–0.8m deep on the ground would be a critical situation for safety evacuation through car doors.

(2) The relationship between the critical depth conditions for the safety evacuation and the subjects' age is investigated based on the participatory test results of the door model by male subjects. The relationship between the critical depth conditions and the male subjects' age is well reproduced by the multiple regression model with the Physical Fitness Survey results of grip strength, sit-ups, and standing long jump.

(3) It is also pointed out based on the estimation results of female subjects that the multiple regression model using the Physical Fitness Survey results has

applicability to the estimation of the critical depth condition in the case of paucity of available data. However, inadequate number of available data is an issue to be resolved to improve the understanding of the relationship between the critical depth conditions and the subjects' age.

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