EVACUATION CHARACTERISTICS OF GROUP WITH WHEELCHAIR USERS

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ABSTRACT

A series of evacuation experiments were conducted on groups of 20 to 24 students including wheelchair users with an aid in walkways. Through these experiments, the effects of the number ratio of wheelchair users to total number of people, width of walkway, and width of opening on such evacuation aspects as the density, flow coefficient of doorways and walking velocity are quantified. Effective evacuation of crowds including the handicapped in public buildings is derived based on the experiments.

KEYWORDS: Evacuation, Wheelchair, Crowd velocity, Crowd density, Flow coefficient

INTRODUCTION

In Japan, there are increasing number of *barrier-free* buildings with the continuous revision of code, so that more elderly and disabled persons can access public buildings more easily. The data such as crowd walking velocity and flow coefficient based on the observation of crowds of normal persons by Togawa [1] are used in Japanese evacuation safety design. It is necessary that elderly and wheelchair users should also be considered together with normal persons in future evacuation safety design. Bearing in mind that with the aging population, *barrier-free* buildings can enable the elderly and disabled persons to access more easily.

The purpose of this paper is to study the flow properties of crowd including wheelchair users with an aid. Hospital and social welfare facilities have an overwhelming number of people who cannot evacuate by themselves and evacuation is influenced by aided capability, which is excluded in the target of the buildings to be unsuitable as general evacuation behavior. There are very few wheelchair users who are ‘walking’ by themselves in public buildings except in hospital and social welfare facilities where there is an aid.

EXPERIMENTAL METHODS

The Experiments

Experiments were conducted with college students from 2003 to 2006. The students were divided into three groups. Individual walking behavior in an indoor walkway in a campus, and crowd walking behavior were videotaped for analysis. The subjects were male and female students from 19 to 25 years old without any physical disability. The experiments were conducted in the season from spring to early summer. The subjects were not wearing many layers of clothing but just light clothing. An individual sitting on a wheelchair was moved with an aid. The wheelchair subjects were selected from the ones with individual walking velocity near the value after subtracting the standard deviation from each group average.

Individual Walking Experiment

The time taken to walk a distance of 15 m or 20 m on a straight walkway was measured by a stopwatch by the subjects themselves. Two types of walking were selected, normal condition with nothing in hand; and moving an individual sitting on a wheelchair with an aid.

Group Walking Experiments Including Wheelchair Users

There were 24 persons in a group. The subjects were arranged to study the effect of including the presence of wheelchair users and the number ratio of wheelchairs, as shown in Fig. 1. The experimental walkway is shown in Fig. 2. The subjects had a stopwatch themselves. They started to walk simultaneously with the signal of start, and measured the walking time from the starting line to the finishing line by themselves, as shown in Fig. 2. The width of the walkway is from 1.2 to 2.0 m wide, an approach run section was prepared short of the starting line to increase density. For the 2.0 m wide walkway, there was not an approach run section, as the width of the lining up condition and the walkway are similar, so the lining up point became the starting point.

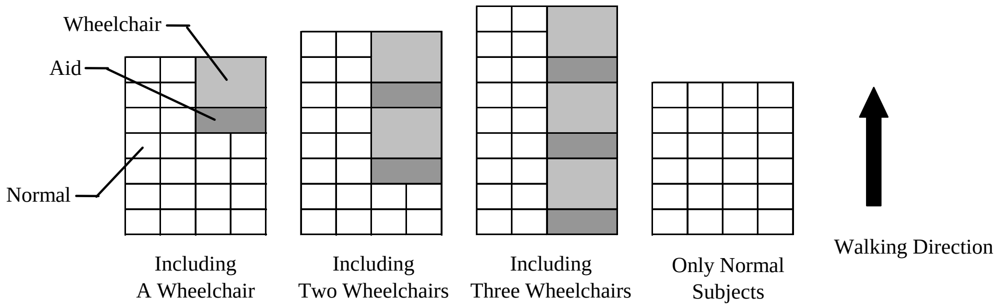


FIGURE 1. Arrangement pattern of group

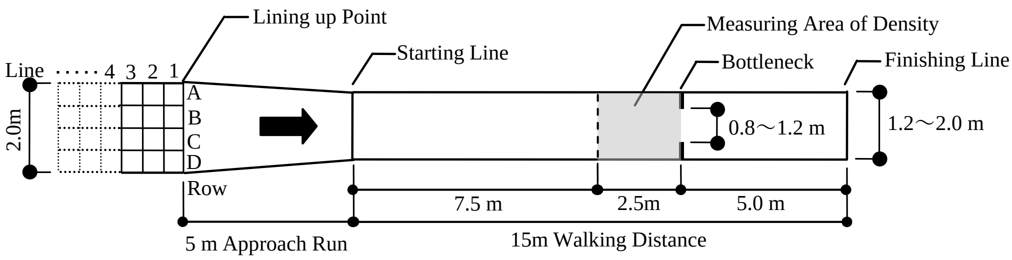


FIGURE 2. Outline of experimental walkways

TABLE 1. Experimental condition of each year

Year	Group Number	Condition of Experiment	
		Width of Walkways [m]	Number of Wheelchairs
2003	All Groups	2.0	from 0 to 2
2004	All Groups	1.7	from 0 to 3
2005	All Groups	1.4	from 0 to 3
2006	Groups from No.2 to No.4	1.2, 1.4, 1.6, 1.8	from 0 to 2

In addition, the group experiments were conducted in school hours, as shown in Table 1. In the experiments of 2003 and 2004, the side walls of walkways were built by corns at worksites. A walkway of 2.0 m wide was used in the experiment in 2003 and a 1.4 m wide walkway in the experiment in 2004, but the subjects' shoulders protruded from the walkway, as shown in Fig. 3. So, the actual width of the walkway was 2.3 m wide in the experiment of 2003 and 1.7 m wide in the experiment of 2004. Because of this, the side walls were changed to 1.6 m high poles with plastic tape in order that the subject shoulders did not protrude from the walkway, as shown in Fig. 4.

FIGURE 3. Protrusion conditions in walkways

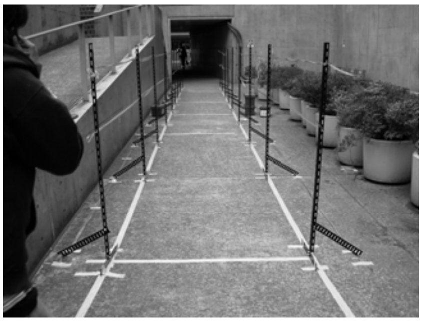


FIGURE 4. Setting up of side wall by poles

The density was measured in the hatched area as shown in Fig. 2. If wheelchairs were included in the group, normal persons passing the wheelchairs directly after start could walk freely, which would decrease the density. So, the measuring time was after the front of a wheelchair passing the 10 m line, until the last one in the group passing the 7.5 m line. For the group with only normal persons, the measuring time was after the front of the group passing the 10 m line, until the last one in the group passing the 7.5 m line. The number of subjects in the measuring area for density was measured every 0.5 second by the video taken. An area taken up by a wheelchair was subtracted from the measuring area of density as shown in Fig. 2. Dividing the value by the number of normal subjects in the measuring area of density would give the density for every 0.5 second.

Experiments of Flow at Doorway with Wheelchair Users

Compared with a normal subject, occupancy area required for a wheelchair to move along is large. The situations different from the groups with only normal persons were considered, wheelchair users with aids were included in a group.

The experiments of passing through doorways were conducted in 2005. The arrangement patterns of groups are similar as in Fig. 1. As shown in Fig. 2, a bottleneck was assumed at the doorway on the experimental walkway, the time passing through the doorway was measured. In the experiment with a 1.4 m wide walkway, the width of the doorway was changed from 0.8 to 1.2 m. Side walls were set up as in Fig. 4. The doorway on the walkway was set up by piling up plastic tool boxes up to about 1.5 m high as shown in Fig. 5. The method of calculating the density is similar to the group walking experiments.

FIGURE 5. Bottleneck on the walkway

RESULTS AND DISCUSSION

Individual Walking Velocity

The total number of subjects was 202 male and 75 female. By excluding the subjects whose walking velocity was especially slow or fast, the individual data of normal subjects of 200 male and 73 female; 196 male and 72 female with wheelchair users were analyzed. It is considered that age and gender become the main parameters to influence the walking capability of subjects. The experimental results were expected to be influenced by gender very much, because the experimental subjects were men and women aged from 19 to 25. So, the *t*-test of gender difference was conducted on the walking velocity of normal persons and wheelchair users with an aid. The result is shown in Table 2. The gender difference of walking velocity of wheelchair users was not found on level of 5 % significance, but difference was found for the normal persons. It is difficult to consider that gender would influence walking velocity, as the average difference for the normal persons is only 0.06 m/sec. So, it is not necessary to consider the gender difference in the analysis of experimental results.

TABLE 2. Result of *t*-test

Walking Pattern	Normal		Wheelchair	
Sex	Man	Woman	Man	Woman
Average [m/sec]	1.33	1.27	1.06	1.06
Standard Deviation [m/sec]	0.17	0.14	0.17	0.18
Variance	0.03	0.02	0.03	0.03
Sample Numbers	200	73	200	74
Degrees of Freedom	271		272	
t-Value	2.52		0.06	
Result	Rejection		Acceptance	

The frequency distribution of walking velocity of normal persons and wheelchair users is shown in Fig. 6. According to Fig. 5, as the distribution of the walking velocity of normal persons and wheelchair users deviated from the normal distribution, the walking capability of wheelchair users could not be explained only by the average difference of walking velocity. As an analysis of *t*-estimation of the population mean in a coefficient of 95% confidence from these data, the walking velocity of normal persons was from 1.29 to 1.33 m/sec and that for wheelchair users was from 1.04 to 1.08 m/sec. This result indicated that the individual walking velocity of wheelchair users decreased by about 0.3 m/sec compared with normal persons.

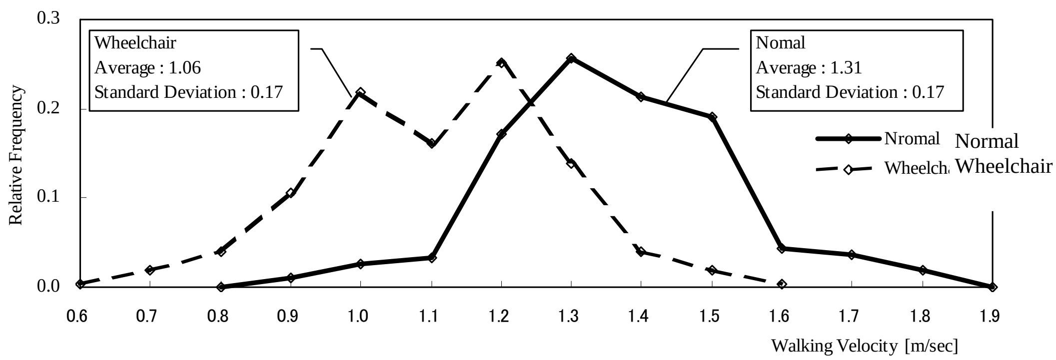


FIGURE 6. Frequency distribution of walking velocity

Group Walking Properties

The relationship between individual walking velocity of normal persons and in groups is shown in Fig. 7. The walking velocity of normal persons in groups decreased compared with the individual walking velocity, as shown in Fig. 7 (a) and (b). It is considered that walking adjustment or stride is restricted when walking in groups in congestion. On the other hand, the walking velocity of wheelchair users in groups increased compared with the individual walking velocity, as shown in Fig. 7 (c). It is considered that the aid adjusted the walking velocity to conform to the surrounding normal persons.

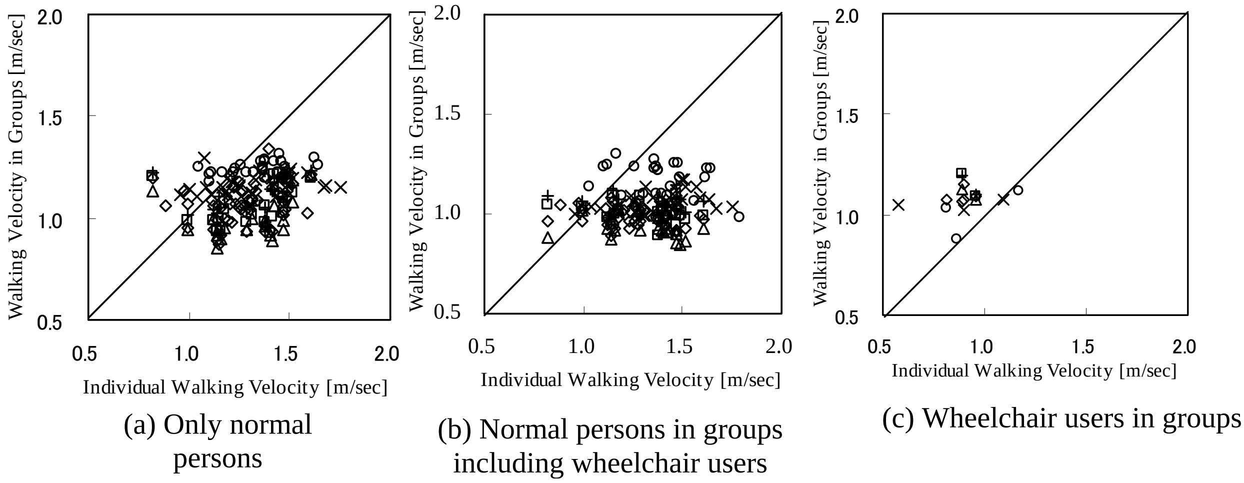


FIGURE 7. Relationship between individual walking velocity and in group

Definition of Crowd Density and Crowd Walking Velocity

The time changes of density are shown in Fig. 8. For the group with only normal persons, the density did not change steeply except in the first half of the measurement. The reason to which the density became low in the first half is that normal persons in the front were able to walk freely, so the walking velocity of each subject differed widely. The density was stable within the range of about 1 person/m^2. For the groups including wheelchairs, the density was not stable, as the first half part is low compared with the second half part. The reason that it would be hard to walk around the wheelchairs in crowding, which makes the density low and the first half part was not stable.

These results indicate that the average measured density is defined as the crowd density, because the density of only normal subjects is generally stable. Then, the group including wheelchairs might not be stable, but the status of the whole group is not indicated by using a part value of density, which defines it as *crowd density* in a similar way as for the groups with only normal persons.

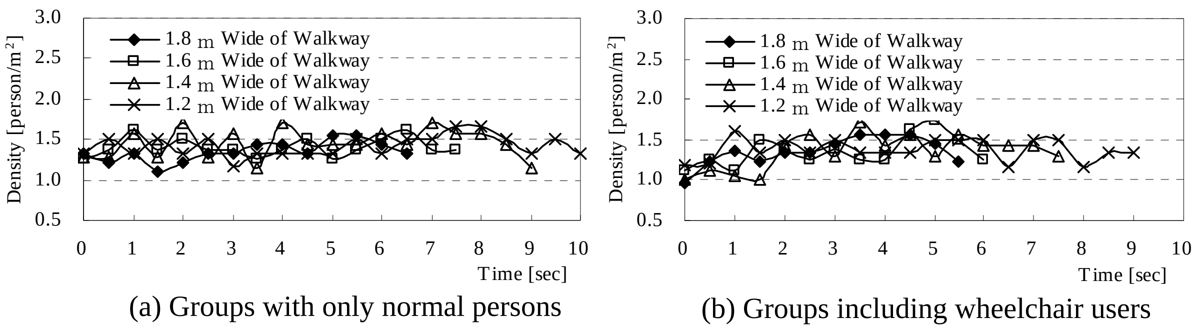
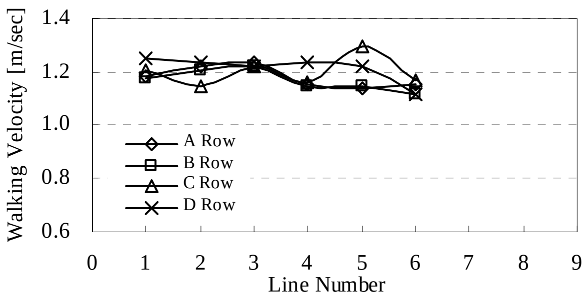
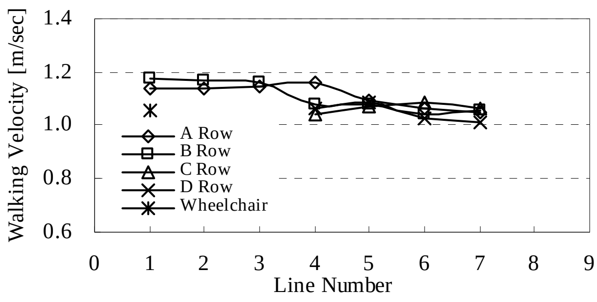


FIGURE 8. Examples of density on group walking behaviour

The walking velocity of each line for group 2 in the experiment in 2004 is shown in Fig. 9. For groups with only normal persons, the walking velocity of persons at the back decreased compared with the persons in the front, which converged to a constant gradually. The convergent value is about 1.1 to 1.2 m/sec. On the other hand, groups including wheelchairs are similar to the groups with only normal persons, which restricts the walking velocity of the persons at the back to the walking velocity of wheelchair users. These results indicate that the walking status is more stable for the persons at the back. So, the walking velocity of normal persons at the back typifies the walking status of the group, which defines the average of four persons at the back as the *crowd walking velocity*.



(a) Groups with only normal persons



(b) Groups including wheelchair users

FIGURE 9. Examples of walking velocity in each line (Group 2 in 2004)

Influence of the Presence of Wheelchair Users

The walking velocity of wheelchair users decreased by about 0.3 m/sec on average. On the basis of this tendency, the subjects that the individual walking velocity on wheelchair with an aid is about the value subtracting the standard deviation from the average of each group were chosen to show clearly the influence by the difference of the walking capability between wheelchair users and normal persons. But the result indicated that the walking velocity of wheelchair users in groups increased compared with individual walking velocity, the cases were also faster than with normal persons. Such groups were excluded to be unsuitable for the analyses that the difference of the walking capability between normal persons and wheelchair users influences crowd walking.

There are many past studies on crowd walking of only normal persons, as the decision factor of crowd walking velocity, relationship to crowd density is shown, but the crowd including wheelchair users would be different. So, concentrating on the parameters such as whether wheelchair users are included, and the width of walkway, the relationship to crowd walking velocity was studied.

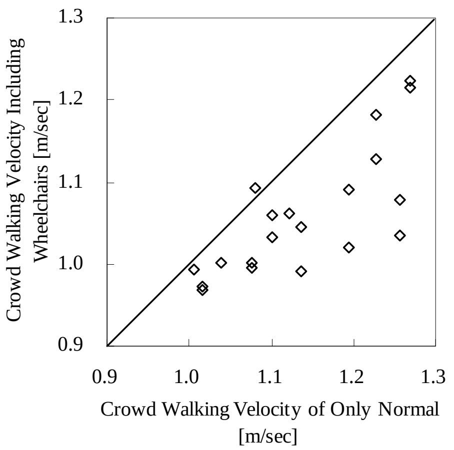


FIGURE 10. Crowd walking velocity of a group with and without wheelchair users

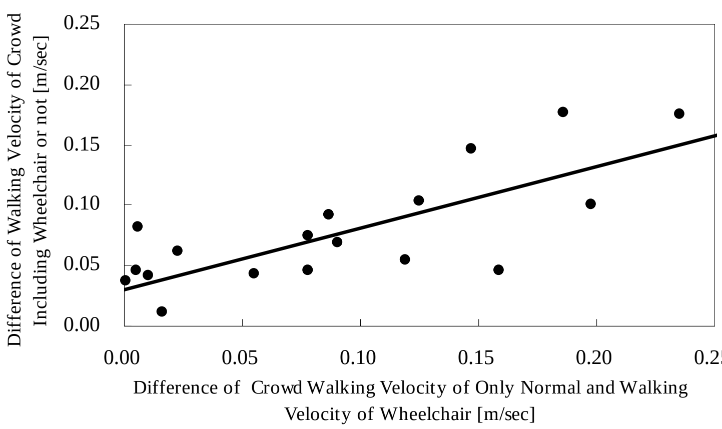


FIGURE 11. Relationship between walking velocity of wheelchair users and crowd walking velocity

As seen in the relation between the walking velocity of crowds with and without wheelchair users in Fig. 10, including wheelchair users in a crowd obviously reduces the crowd walking velocity. Wheelchair users may affect the group walking behavior through differences in walking velocity and the area to occupy. Fig. 11 is a summary of the correlation between the difference in walking velocity of individual normal persons and wheelchair users and that of the groups with and without wheelchair users, which yields a positive correlation with the *t*-test analysis level of 0.05 significance. This indicates the significance of including slow-walkers in a crowd on the crowd walking velocity.

Another aspect of wheelchairs that may influence the crowd walking behavior is that its width is wider than the human body. While the wheelchairs used in the experiments and a human body are 0.6 m and around 0.5 m wide respectively, exercise suggests that 1.0 m and 0.8 m are necessary for a wheelchair and a man respectively to move freely. The experimental walkway is narrower than the sum of these, which implies possible conflicts when a normal subject tries to overtake a wheelchair user on the 1.2 m wide experimental walkway. In order to look closer into how the width of wheelchair affect the walking behavior of normal subjects, the birds eye pictures as in Fig. 12 are analyzed.

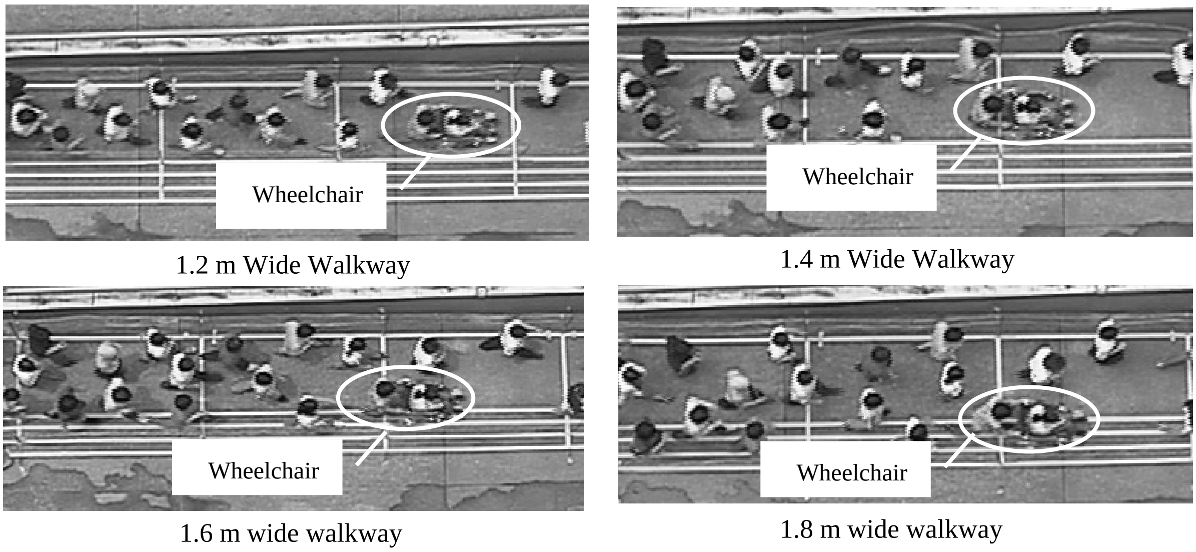


FIGURE 12. Circumstances of overtaking wheelchair users by a normal person

In the 1.2 m wide walkway, a normal person would be impossible to overtake a wheelchair user. As far as checking the birds eye pictures, there were enough spaces to overtake a wheelchair user for the 1.4 to 1.6 m wide walkways, but overtaking did not appear actually. In walkways from 1.7 m to 2.3 m, there were enough spaces to overtake a wheelchair user, which also often appeared.

According to the walking width of a wheelchair and the width of a walkway, a normal person could not overtake a wheelchair user indicated that the crowd walking velocity including wheelchairs decreased. The relationship between the crowd walking velocity and the width of walkway is shown in Fig. 13.

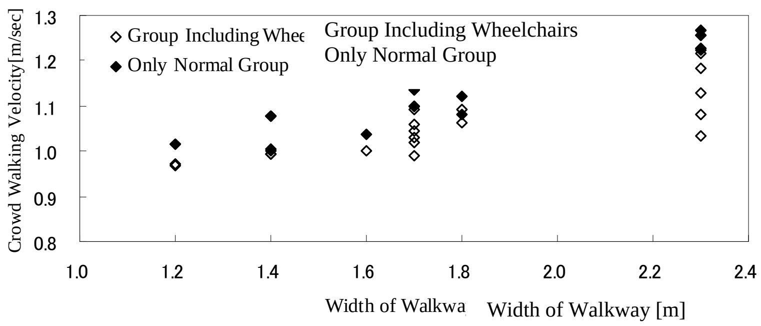


FIGURE 13. Relationship between crowd walking velocity and width of walkway

Regardless of whether or not wheelchairs were included, the width of walkway and the crowd walking velocity showed a positive correlation. From the analysis of *t*-test, it was found in the level of 0.05 significance. So, the relationship between the crowd walking velocity and the width of walkway was not only found in groups including wheelchairs, which indicated that the influence of the walking width of a wheelchair could not be explained only by this relationship. If the width of a walkway becomes narrow, the normal person would not be able to overtake the wheelchairs, which indicated that the crowd walking velocity would be the walking velocity of the wheelchair users. The relationship between the subtraction of the crowd walking velocity to the walking velocity of wheelchair users in groups and the width of walkway is shown in Fig. 14. If the width of the walkway becomes narrow, the normal person could not overtake the wheelchairs, which revealed that the crowd walking velocity would be the walking velocity of the wheelchair users.

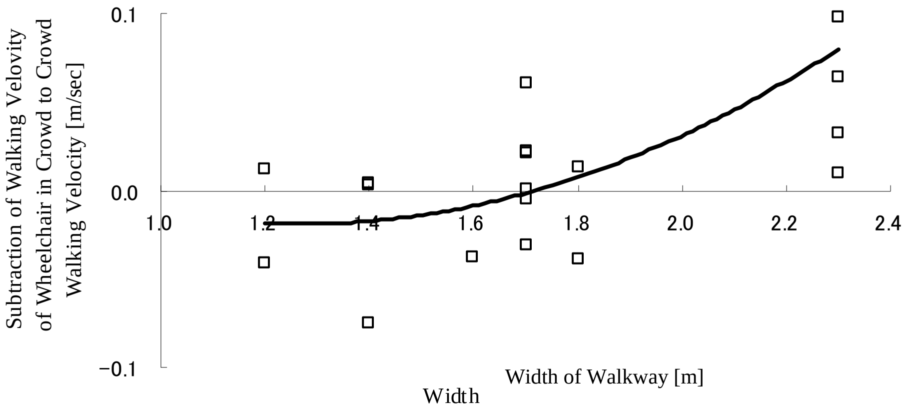


FIGURE 14. Relationship between subtraction of walking velocity and width of walkway

Prediction of Crowd Walking Velocity Including Wheelchair Users

The above analysis indicated that the crowd walking velocity including wheelchair users decreased more than the crowd with only normal persons by the influences that the walking velocity of wheelchair users is slower and the width of walkway is narrower, a normal person is difficult to overtake the wheelchairs. These phenomena would be verified by the following model, if the decrease in the crowd walking velocity by including wheelchairs would be shown by these factors.

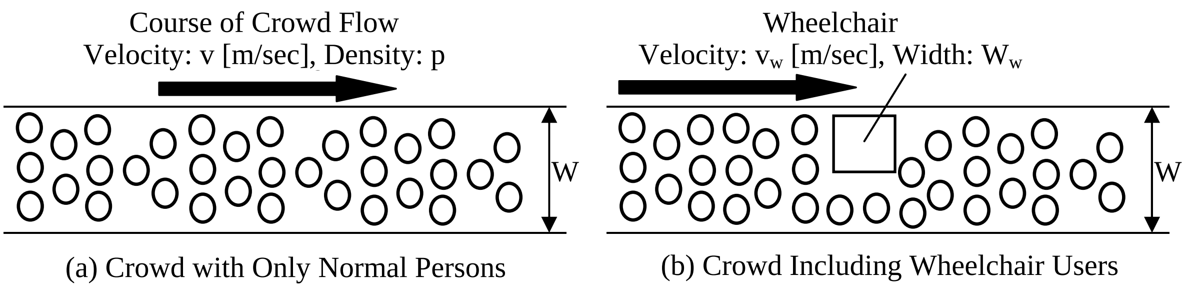


FIGURE 15. Concept of crowd walking model

The concept of crowd walking model is shown in Fig. 15. It is assumed that the crowd with only normal persons are walking on a w [m] wide of walkway with crowd density p [person/m^2]. The walking velocity is v [m/sec] which depends on the crowd density. For the crowd with normal persons and the wheelchair users of walking velocity v_w [m/sec], walking width w_w [m] is assumed to include the crowd, and the walking velocity of the wheelchair users is slower than the crowd walking velocity. The normal persons were assumed to walk pass the wheelchair by $v > v_w$. In such condition, the number of normal persons per unit time N [person/sec] passing at the side of the wheelchair is shown as the following equation [1], as the crowd density behind the wheelchair users would not change.

$$N = p(v-v_w)(w-w_w) \quad [1]$$

On the crowd of density p [person/m^2], the number of persons per unit length in the w [m] wide walkway becomes pw [person/m]. If the crowd is always assumed to walk in uniform density, the reciprocal number of pw [person/m] becomes the velocity per the number of persons passing at the side of the wheelchair to advance the crowd. As the product of the advance velocity per the number of persons passing at the side of the wheelchair and an equation [1], the relative crowd walking velocity v_r [m/sec] to the walking velocity of wheelchairs is shown as the following equation [2].

$$v_r = (v-v_w)(w-w_w)/w \quad [2]$$

The crowd walking velocity v [m/sec] is calculated to add the walking velocity of the wheelchair to an equation [2], as shown in equation [3].

$$v = v_r + v_w = (v-v_w)(w-w_w)/w + v_w \quad [3]$$

The calculated value and the experimental value were compared to confirm the effectiveness of an equation [3]. In these parameters, for w_w of 1.2 m, it would be impossible for the normal person to overtake the wheelchair on a 1.2 m wide walkway. It might approach the value about the exact size of the wheelchair, it is completely impossible to overtake the wheelchair on the 1.2 m wide walkway from the observation as recorded in the videos, which indicated that the lower of w_w would be about 1.2 m wide. v is the walking velocity of the crowd of the same subjects without including the wheelchair users, and the walking velocity of the wheelchair users increased a little in crowd, which substituted the walking velocity of the wheelchair user in the crowd for v_w. The relationship between the calculated value and the experimental value is shown in Fig. 16.

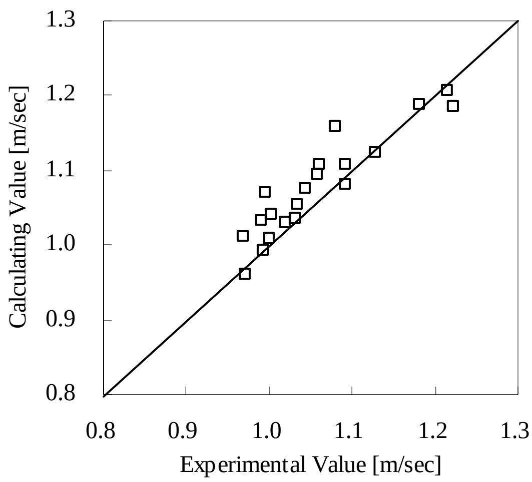
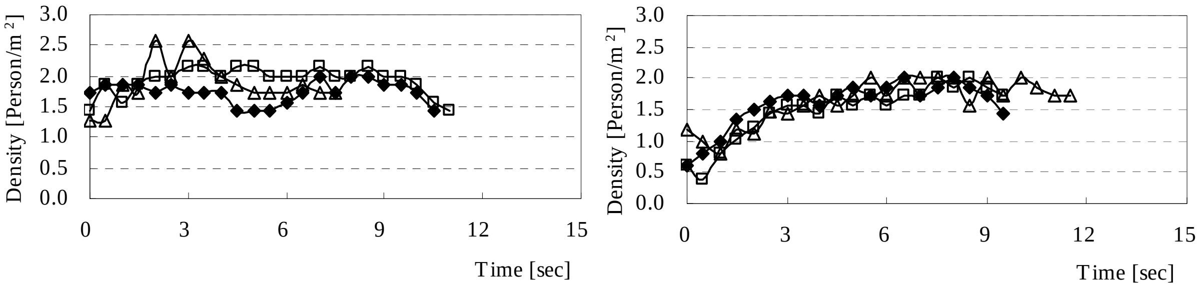


FIGURE 16. Correlation between the calculated value and the experimental value

The calculated value agrees well with the experimental value with a coefficient of correlation of 0.92, mean error –0.02, but it is shown that the experimental value is lower than the calculated value. So, the crowd walking velocity including wheelchairs could be estimated by equation [3], if the walking width of a wheelchair is established according to the condition on passing wheelchairs. After all, the above analysis revealed that the crowd walking velocity of including wheelchairs is determined by the walking velocity of wheelchairs and the width of the walkway.

Crowd Density and Flow Coefficient at Doorway

The example of the crowd density on passing through a doorway of 0.9 m wide is shown in Fig. 17. It has the similar tendency as that for no doorway, which defines it as the *crowd density*.



(a) Group with only normal subjects (b) Group including a wheelchair

FIGURE 17. Example of group density on passing through a 0.9 m wide doorway

According to the theory of traffic flow, there is a relationship between the number of persons passing through the doorway and the crowd density as in Fig. 18, N_{max} in the figure is the flow coefficient as the passing capability of the doorway. The number of people passing through should be measured on crowd density more than certain quantity in order to grasp the maximum passing capability of the doorway. If there is a doorway on the walkway, queuing appears near the doorway, which increases the crowd density near the doorway. It will be difficult to derive the flow coefficient as the passing capability, if the positive correlation between the density and the passing quantity appears only.

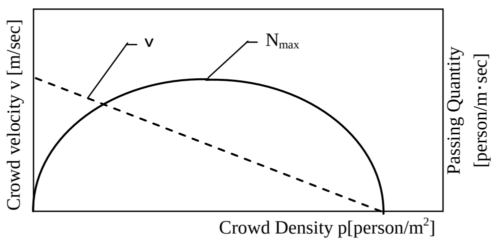


FIGURE 18. Relationship of flow rate and crowd density by theory of traffic

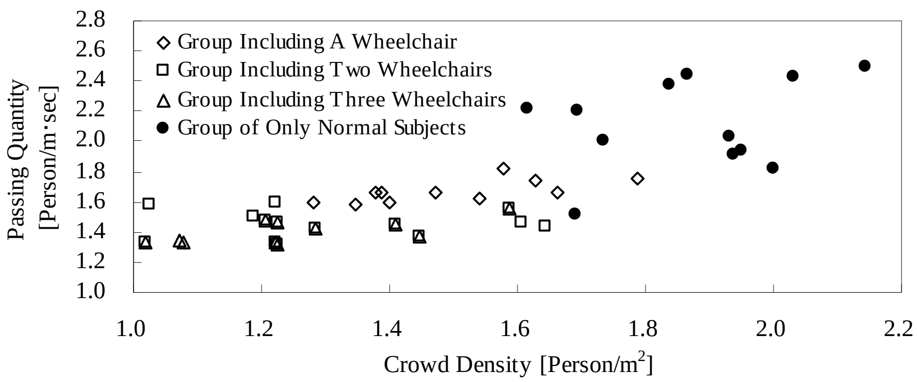
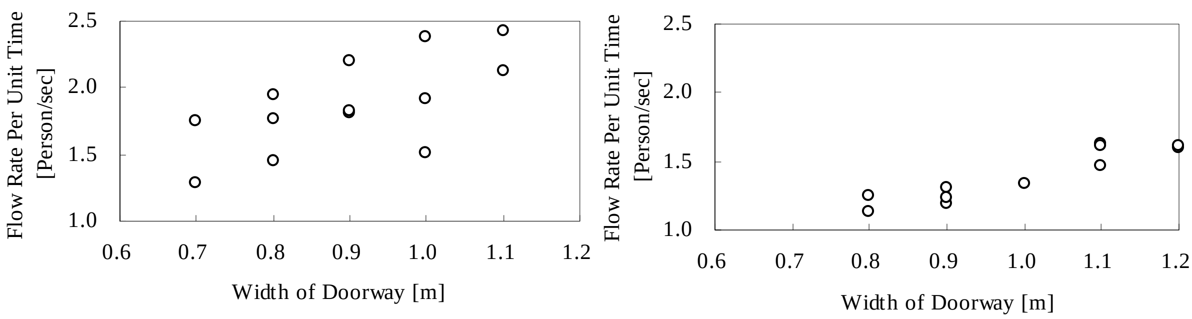


FIGURE 19. Relationship of average flow rate and crowd density

The relation between flow rate and crowd density is shown in Fig. 19. For the group with only normal subjects, both the crowd density and the flow rate are high compared with the group with wheelchair users, the flow rate increased with increasing crowd density. For the group including wheelchairs, the flow rate does not change much regardless of the number of wheelchairs, which indicates that N_{max} in Fig. 18 would appear.

Regarding the influence on the crowd flow by the doorways of buildings, Okada et al. [3] pointed out that the crowd flow is not only the fluid motion but also the grain motion, and the relationship between the width and the flow rate is not directly proportional, because each human body is wide enough compared with the doorways, if the human body size is assumed to be a unit width, the proportional relation applies to integral multiplies per unit width. If this is right, wheelchair will be very different from the human body size, and the unit width of a wheelchair should be established too. The relationship between the flow rate per unit time and the width of doorway is shown in Fig. 20.



(a) Group with only normal subjects

(b) Group including three wheelchairs

FIGURE 20. Relation of flow rate per unit time to width of doorway

Okada et al. [3] have recommended the value of 0.55 m as the unit width of a human body, it is considered to show shoulder width. If the concept of the unit width of a human body is right, the flow rate per unit time should not change in crowds with only normal persons as shown in Fig. 20(a). But the result shows proportional relation between the width of doorway and the flow rate per unit time, indicating that the passing efficiency increases even when a doorway changes about 0.1 m wide. The concept of unit width might only consist of human flow in doorways on facing the front. The observation of birds eyes pictures has flow on turning shoulders, and might have psychological influence on which is easy to flow in doorways. These analyses indicate that the flow rate is established by the unit width of doorway, when studying the flow rate in crowding around doorways.

The crowd including wheelchairs has also a proportional relation between the width of walkway and the flow rate per unit time. According to the observation of pictures, parallel passing of the normal persons and wheelchairs appear only for the 1.1 m to 1.2 m wide doorways, the normal persons passed barely on turning shoulders. If the unit width of a wheelchair has an effect, the proportional relation between the width of doorway and the flow rate per unit time should change remarkably for the 1.1 m wide doorway, but such tendency could not appear in the crowd including three wheelchairs. It was considered that wheelchairs would not be limber to the behavior on passing doorways, but the behavior would change limberly as changing the width of doorway, like the passing velocity of wheelchairs increased with the increasing width. These analyses indicated the flow capability per unit width of doorway in the crowd including wheelchairs would not change from 0.8 to 1.2 m wide doorways.

In the above analyses, the relationship between the flow coefficient at the doorway and including the number of wheelchairs is shown in Fig. 21. In the calculation of the flow rate, a wheelchair is calculated as two persons. The flow coefficient measuring the flow capability of the doorways are shown, and the flow rate for the front of a wheelchair started to pass through the doorway was measured, the normal person passed before the wheelchair was excluded in the number of measurement. The flow coefficient decreased with the increase of the number of wheelchairs in the crowd. Compared with the crowd with only normal persons that could keep the flow state, the crowd flow was separated and wheelchairs took more time to pass through the doorway than the normal persons, which indicated that the flow coefficient decreased with the increase of the number of wheelchairs. The flow coefficient for the group including three wheelchairs was about 1.3 person/m・sec.

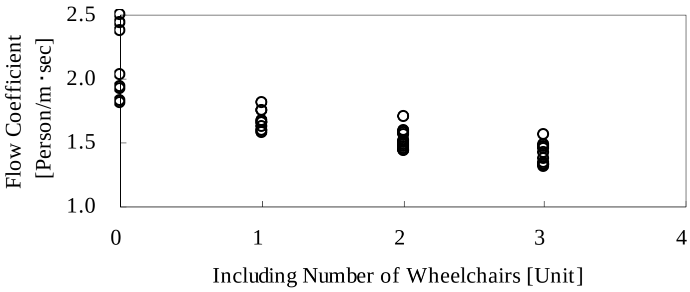


FIGURE 21. Relationship between the flow coefficient and the number of wheelchairs

CONCLUSIONS

In this study, the flow properties on crowds including wheelchairs with an aid were studied. If wheelchairs with an aid were included in the crowd, the crowd walking velocity decreased compared with crowd with only normal persons. If the width of the walkway is large, normal persons can overtake the wheelchairs and the crowd walking velocity increase. These analyses suggested the predicted equation for the crowd walking velocity including wheelchairs with an aid.

When wheelchair users in a crowd pass through a doorway, both the crowd density and flow coefficient decrease compared with the crowd with only normal persons. Whether or not wheelchairs are included has a great influence on the flow coefficient, which decreases the flow coefficient slowly. Therefore, the flow coefficient on including three wheelchairs became about 1.3 person/m・sec. At present, the flow coefficient used in Japanese evacuation safety design is 1.5 person/m・sec, which indicates that the flow capability decreases by about 15 % if wheelchairs are included.

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