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An experimental study of visibility effect on evacuation speed on stairs

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ABSTRACT

Staircases are key structures in vertical evacuation in buildings. In this work, individual upward evacuation experiments in staircases under four visibility conditions were performed to study the evacuation speed for both male and female pedestrians. The relationship between evacuation speed and floor level was analyzed. It was found that the influence of visibility was much more significant on the females than on the males. Group upward and downward evacuation experiments were also conducted. With the decrease of visibility, the evacuation time increased first and then became equal gradually. Under synergistic effect of visibility and evacuation distance, the visibility became the most important factor influencing the evacuation speed. A relationship model between evacuation speed and population density was developed through statistical methods, which was compared with the model in the SFPE Handbook.

1. Introduction

Staircases are key structures in vertical evacuation in buildings. The evacuation characteristics on stairs have caught the attention of scholars since the 1960s [1–3]. With the rapid development of the economy, lots of multi-story buildings and high-rise buildings were built. Long-distance evacuation has attracted more and more attention. Individual and group evacuation speed was investigated in a lot of studies [2,4–9], as listed in Table 1. In 2008, Kretz et al. investigated the individual and group upward walking speed at the long stairway of the Dutch pavilion at Expo 2000 in Hannover [4]. The average speed ranged from 0.44 m/s to 0.52 m/s. In 2009, Yeo and He studied the evacuation characteristics in mass rapid transit (MRT) stations in Singapore [5]. In 2014, Lam et al. conducted an evacuation experiment in a high-rise residential building in Hong Kong. It was found that the average upward speed ranged from 0.48 m/s to 0.52 m/s [6]. In 2014, Choi et al. investigated the individual ascent speeds of Korean students [7]. The results showed the average ascent speed was 0.75 m/s for the males and 0.53 m/s for the females on the first 20 floors. On the last 20 floors, the average speed was 0.55 m/s for the males and 0.42 m/s for the females. Ronchi et al. studied the walking speed in long stairways in Sweden in 2015 [8]. The median individual ascent speed ranged from 0.66 m/s to 0.87 m/s, and the median group ascent speed ranged from 0.52 m/s to 0.83 m/s. In 2016, Chen et al. conducted an experiment in a 26-level typical residential building in China [9]. It was found that the ascent speed decreased continuously on the first 13–14 floors. After the 14th floor, the ascent speed was around 0.68 m/s for the males and 0.52 m/s for the females.

Due to numerous casualties caused by the low level of visibility during evacuation, the evacuation behavior characteristics in different visibility conditions have been studied [10–13]. In 1997, Jin conducted several experiments under different visibility conditions to analyze the effect of extinction coefficient (flue gas conditions) on the evacuation speed, the level of visibility and the visual perception [14]. In 1998, Jensen observed the evacuation behavior of 84 participants under different smoke densities. He pointed out that visibility level was a key factor in evacuation [15]. The evacuation speed under different visibility conditions was investigated [16,17,19,21–23,25], as listed in Table 2. From 1999 to 2006, in order to explore the effect of phosphorescent materials on evacuation on stairs, National Research Council of Canada (NRC) investigated the evacuation behavior of 392 people in a 10-story office building, and working jointly with NRC, Public Works and Government Services Canada (PWGSC) carried out experiments on evacuation behavior of 1198 people in a 13-story office building. It was found that using the handrails was a main factor leading to evacuation congestion [16–18]. In 2011, Jeon conducted experiments with 125 people under four different visibility conditions in an underground

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Table 1
Occupant ascent evacuation speeds derived from literature.

Year	Speed (m/s)	General information	Source	Country
1971	0.69–0.81[a]	Males between the age of 30–50	[2]	USA
	0.61–0.65[a]	Females between the age of 30–50		
	0.39–0.45[a]	Males over 50 years old		
	0.41–0.43[a]	Females over 50 years old		
2008	0.52[b]	Single Person	[4]	Germany
	0.47[b]	Group of people (low density)		
	0.44[b]	Group of people (high density)		
2009	0.29[c]	Children	[5]	Singapore
	0.27[c]	Elderly females		
	0.28[c]	Elderly males		
	0.29[c]	Elderly		
	0.31[c]	Adult females		
	0.32[c]	Adult males		
	0.30[c]	Adults		
2014	0.48[d]	Students (5–9 years old)	[6]	Hong Kong
	0.51[d]	Students (10–19 years old)		
	0.52[d]	Different occupations (20–40 years old)		
	0.47[d]	Different occupations (41–55 years old)		
2014	0.75[e]	Males, 1–25 floors	[7]	Korea
	0.55[e]	Males, 26–50 floors		
	0.53[e]	Females, 1–25 floors		
	0.42[e]	Females 26–50 floors		
2015	0.67–0.75[f]	Single person	[8]	Sweden
	0.62–0.75[f]	Group of people		
	0.73–0.87[g]	Single person		
	0.70–0.83[g]	Group of people		
	0.66–0.79[h]	Single person		
	0.52–0.80[h]	Group of people		
2016	1.71[i]	Males in the first floor	[9]	China
	0.68[i]	Males after 14 levels		
	1.11[i]	Females in the first floor		
	0.52[i]	Females after 14 levels		

[a] The stairs with a slope of 27° and 32°, respectively.
[b] The stair had a slope of 35.1° and was 35.8 m high. The speed was measured after 25 m.
[c] Vertical speed. Several short stairs at different metro stations were studied. A total of 643 commuters were analyzed. The slope of the stairs was not known.
[d] The study was conducted in a high-rise residential building with 40 floors above the ground. The stair had a slope of 34°. A total of 120 participants were analyzed.
[e] 60 participants, including 30 males in the age range 20–28 (mean 24.6), 30 females in the age range 20–28 (mean 22.2). The stair had a slope of 32.5°.
[f] The individual experiment involved 47 participants in the age range 19–51 (mean 33), including 27 males and 20 females. The stair had a slope of 34.7°.
[g] The individual experiment involved 29 participants in the age range 20–46 (mean 32), including 16 males and 13 females. The stair had a slope of 32.2°.
[h] The individual experiment involved 34 participants in the age range 22–64 (mean 38), including 21 males and 13 females. The stair had a slope of 26.6°.
[i] 165 college students, including 114 males in the age range 17–22 (mean 18.57) and 51 females in the age range 17–25 (mean 18.41). The stair had a slope of 32°.

4-story subway station to explore the influence of visibility conditions on evacuation in underground facilities [19]. For the first time, flue gas conditions were simulated through wearing eye-patches [19,20]. In 1991, Bellamy et al. studied the evacuation speed under different fire conditions and found that evacuee speed was 0.5–1.0 m/s in smoke-filled subway tunnels without lighting, while in the condition with lighting in the tunnels, the evacuee speed was 1.0–1.45 m/s (specific luminance value and conditions of flue gas were unclear) [21]. In 2007, Boer found that the average evacuee speed was 1.37 m/s in road tunnels with flue and gas (specific flue gas condition was not clear) [22]. In 2000, Galea et al. conducted evacuation experiments in a 37-m-long tunnel [23]. Irritant gases were used to simulate smoke conditions. They concluded that in the absence of light the average evacuee speed was 0.2–0.8 m/s with the smoke dissipation coefficient being 2.0–8.0 m^{-1}. In 2013, using the same simulation method, Fridolf conducted evacuation experiments under different visibility conditions in a 200-m-long tunnel and concluded that the evacuation speed was 0.42–0.81 m/s when the smoke

Table 2
Occupant evacuation speeds derived from various visibility experiments.

Year	Mean speed (m/s)	General information	Source	Country
2006	0.66[j]	The stairway in normal condition, down	[16]	Canada
	0.40–0.66[j]	The stairway only had photo-luminescent material, down		
2010	0.70[k]	The stairway in emergency lighting (57 lux), down	[17]	Canada
	0.61[k]	The stairway in fulling lighting (245 lux), down		
	0.57[k]	The stairway only had photo-luminescent material, down		
	0.72[k]	The stairway only had photo-luminescent material and in lighting (74 lux), down		
2011	1.34–1.69[l]	The experiments in normal condition, up	[19]	Korea
	1.23–1.61[l]	The experiments in lighting out condition, up		
	0.62–0.64[l]	The experiments in slight hindrance, up		
	0.51–0.62[l]	The experiments in heavy hindrance, up		
1991	0.5–1.0	Road tunnel with some smoke, no lighting, horizontal	[21]	UK
	1.0–1.45	Road tunnel with some smoke, emergency lighting, horizontal		
2007	1.37[m]	Road tunnel with some smoke, horizontal	[22]	Euro
2000	0.2–0.8[n]	Road tunnel with irritant smoke, no lighting, horizontal	[23]	–
2013	0.81–0.84[o]	Road tunnel with artificial smoke and acetic acid (mean light extinction coefficient was 2.2 m^{-1}), horizontal	[25]	Sweden

[j] The study involved about 1191 participants. The slope of the stairs was not known.
[k] The study involved 392 participants. The stairs were 1.1 m in width with step riser of 0.18 m.
[l] The study was conducted in an underground subway station, involved 125 participants in the mean age of 34.3 years old. The slope of the stairs was not known.
[m] The tunnel was 1 km long.
[n] The study involved about 30 participants. The experiment location was not known.
[o] The study involved100 participants. The experiment tunnel was 200 m long.

dissipation coefficient was 2.2 m^{-1} [24,25].

Among all the previous research, only Jeon and NRC studied the effect of visibility on evacuation behavior on stairs. However, in Jeon's research, the experiments were performed in an underground 4-story subway station. As the subway station was not very deep, most evacuation inside was horizontal. Therefore, the results were not valid for long-distance evacuations on stairs. NRC carried out experiments in a 10-story office building. However, NRC did not perform upward evacuation experiments and did not consider the effect of flue and gas conditions on evacuation speed. Therefore, it is urgent to investigate the effect of visibility on evacuation speed on stairs and build an evacuation model in different visibility conditions.

In this work, evacuation experiments for both individuals and groups in four different visibility conditions were performed. Four visibility conditions were designed: (1) participants did not wear eye-patches and the stairs had lighting (**Condition 1**), referring to the normal condition; (2) participants did not wear eye-patches and there was no lighting (**Condition 2**), referring to the condition in which the lighting failed while evacuees were not affected by the flue and gas conditions; (3) participants wore eye-patches with light transmittance of 27% (**Condition 3**), referring to the situation that evacuees were affected slightly by smoke; (4) participants wore eye-patches with light transmittance of 16% (**Condition 4**), referring to the situation that evacuees were severely influenced by smoke.