

Doctoral Thesis

**The Numerical Analysis of Mass Evacuation of
Super High-rise Buildings with Control Volume Model**

March 2020

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TOKYO UNIVERSITY OF SCIENCE

博 士 論 文

コントロールボリュームモデルによる 超高層ビルの大規模な避難の数値解析

2020年3月

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Abstract

The emergency event challenges of super high-rise and high-rise buildings are always a major concern to the life safety of occupants due to the extended vertical travel distance and the elevated height for egress and means of access. Egress system, in concern with evacuation plans, human behaviors, and crowd management form the basis of safety design for emergency events. In this study, the numerical results and dynamic processes of mass evacuation of a super high-rise building are investigated by using the control volume model. The super high-rise building, Taipei 101 is chosen for the object of evacuation simulation building, which is about 508m tall. The control volume model assumes that each individual is an independent particle and a virtual closed surface that can be formed by connecting the waiting persons at exit. One of these basic assumptions of this model was adopted a hydraulic analogy which evacuees were considered as a homogeneous fluid flow during the evacuation process. The simulation process of evacuation modelling in the stairwell is divided into 5 stages and presented. Based on fire drills, the speed characteristics of mass occupants in the stairwells for various floor intervals are investigated in this study. The numerical results of mass evacuation are found to be in good agreement with the result of the National Fire Protection Association (NFPA) first-order approximation and indicate that the evacuation processes are highly dependent on the parameters of walking speed and specific flow. The effects of different walking speed, coefficient of flow rate, and merge flow ratio on the dynamic change and the number of the occupants stagnating for each floor in various time scales are presented and discussed.

Keywords: Evacuation, Super high-rise building, Control volume model, Evacuation simulation

Acknowledgments

I would like to express my deep gratitude to Professor Yoshifumi Ohmiya and Professor Masayuki Mizuno, my research supervisors, for their enthusiastic encouragement, patient guidance, and useful critiques of this research work.

I would also like to thank Professor Kenichi Ikeda, Professor Ichiro Hagiwara, Professor Takashi Seo, and Professor Takashiro Akitsu, the Ph.D. committee members, for their valuable advice and instructions in keeping my dissertation on schedule.

I also appreciate the valuable comments and constructive suggestions given by Prof. Ai Sekizawa.

I would also like to extend my thanks to former President Chien-Sheng Tiao and President Wen-Ming Li of Central Police University for their support to offer me in the academic exchange meeting with Tokyo University of Science.

My grateful thanks are also extended to Mr. Yi-Liang Chien , Mr. Seong-Kyung Park, Mr. Toshinari Tanaka, and Mr. Takumi Otsuka, the members of the laboratory of Professor Mizuno, for their help in offering me the resources of the research affairs.

Finally, I wish to thank my mother, wife, children, friends, and colleagues for their great support and encouragement throughout my study.

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Chapter 1

Introduction

Chapter 1: Introduction

1.1 Introduction of Chapter

Providing for life safety during emergency events is the key aspect of any building and facility design. This chapter focuses on the research background and purposes of this study, provides the methodology and algorithm in this study, as well as a brief overview of pre-movement time, merging behavior, evacuation simulation models, human behavior, evacuation strategy planning, etc. in high-rise/super high-rise buildings. Finally, a review of egress movement of populations in high-rise/super high-rise buildings is provided.

1.2 Research Background

With increasing awareness of the importance of occupant safety and the desire to avoid disorder, the issues of the mass evacuation of super high-rise buildings have raised special attention by the general public and authorities in the world, especially since the WTC 9/11 disaster. Several studies have investigated the recognition, response phases, pre-evacuation delay, and environmental factors of the evacuees of towers 1 and 2 to present detailed behaviors and experiences of large full-scale evacuation, and the results have been published [1-8].

Galea et al. provided a broad overview of project HEED (High-rise Evacuation Evaluation Database) and the methodologies employed in the collection and storage of first-hand accounts of evacuation experiences derived from face-to-face interviews of evacuees from the World Trade Center (WTC) Twin Towers complex on September 11, 2001 [1]. Kuligowski and Mileti [2] used path analysis to develop an empirically based, parsimonious explanation (i.e., model) of the key factors and processes that led to occupants' delays in beginning their evacuation from the WTC Towers. In order to extend the generalizability of the findings of Kuligowski and Mileti [2], Sherman et al. [3] used a linear regression model to identify significant predictors of pre-evacuation delay in a sample of evacuees enrolled in the World Trade Center Evacuation Study and found that the relation between emergency preparedness and pre-evacuation delay was positive. Shields et al. [4] focused on the behaviour and experiences of six evacuees of Towers 1 and 2, who declared a mobility impairment in their pre-interview questionnaire. McConnell et al. [5] focused on cue recognition and response patterns within WTC1, they pointed out that results include information regarding cues experienced, activities prior and subsequent to occupants first becoming aware, perceived personal risk, time taken to respond and the inter-

relationships between them. Fahy [6] investigated the evacuation of the two towers, based on an analysis of first-person accounts that began to appear in the media immediately after the incident. Based on surveys and analyses on human behavior in the New York World Trade Center disasters in 1993 and 2001, Yoshida [7] studied measures for life safety design to future tall buildings focusing on a heavy congestion in the stairs caused by simultaneous escape in the whole building.

Of all the buildings, those that exceed 100m or have 30 stories or more are usually classified as super high-rise buildings in Taiwan. For super high-rise buildings, the current evacuation strategies can basically be classified into two main subsets: phased evacuation and total building evacuation. In the phased evacuation, the occupants will be prioritized to evacuate firstly on the most hazardous floors like fire floor and the adjacent floors. The remaining occupants of the building will evacuate subsequently if necessary. In the total building evacuation, while the emergency fire is happening, all building occupants are expected to evacuate to the staircases which lead to the ground floor.

In this dissertation, the results of the numerical analysis of mass evacuation in Taipei 101 for each floor are presented from the 2nd to 91st floor. The numerical algorithm of this proposed method has to derive 90 exits at each time-step simultaneously. The number of prescriptive allowable occupants is 12,200 located on floors 2 to 91. Not only the occupant's distributions are not uniform, but also there are the refuge spaces on the floors in Taipei 101. For example, on the top of each eight-floor section is a mechanic floor. Especially, 17th and 18th floors are the mechanical floor, there will be no exit flow from these two floors, and which postpones the time of merging for the 16th floor's exit flow and the 19th floor's stair flow. Therefore, the "super high-rise buildings" is used to be the topic of this dissertation.

The field of emergency evacuation has already been investigated in the past decades. Analysis based on the actual evacuation fire drill data plays an important part in researching occupant evacuation, but unfortunately these data are not consistent with the real situations. Most of the experimental studies and drills in the literature for evacuation of the super high-rise buildings are analyzed by considering free moving. Especially, our current understanding of how people act during an accident in the staircase of the super high-rise buildings is still limited. One of the complicated problems of the simulation model is the treatment of human behaviors such as crowd flow, counter flow, pre-movement delay, exit choice, decision making, physical factors, disabilities, and psychologies in emergency situations, etc.

1.3 Research Purposes

For the evacuation safety of high-rise buildings in Japan [9] and Taiwan [10], the total egress time of the performance approach can be obtained by three categories, i.e. the starting time, the traveling time, and the queuing time. This performance approach which is associated with the means of the verification method of evacuation safety and evacuees is considered as a homogeneous fluid. Meanwhile, the consequence of the performance approach for the evacuation of a super high-rise building is led to a fixed value of time only.

The main aim of this study is to establish the evacuation modeling to investigate the numerical analysis of mass evacuation in a super high-rise building with the control volume model [11-13]. This includes the proper assumptions in modeling emergency evacuation as well as using the suitable movement parameters.

In order to achieve this aim, literature reviewing, experimental drill data collecting, and scenario analysis of emergency evacuation modeling are applied to this study. Based on fire drills, the speed characteristics of occupants when evacuating down in the stairwells of super high-rise buildings for various floor intervals have been obtained and analyzed. By varying the values of movement parameters, the effects of these parameters such as merge flow ratio, coefficient of flow rate, and walking speed on the whole processes of mass evacuation in a super high-rise building are presented investigated.

1.4 The Methodology and Algorithm

In this study, several methods are used to obtain the numerical results of occupant evacuation, movement characteristics, and egress prediction in super-high rise buildings. These methods and are briefly presented as follows.

1.4.1 Literature review

In this study, the literature review involves collecting published articles related to the topics of the evacuation process such as pre-movement time, merging behavior, evacuation simulation models, human behavior, evacuation strategy planning, egress movement, etc. in high-rise/super high-rise buildings, and analyzing what can be learned through considering these collectively. The following resources that are used: journal databases, subject specific professional websites, and domestic regulations.

1.4.2 The control volume method

The main aim of this study is to simulate the dynamics of the evacuees and derive the evacuation times of the high rise building by using the control volume model [11-13]. The control volume model assumes that each individual is an independent

particle and a virtual closed surface that can be formed by connecting the waiting persons at an exit. During the evacuation process, when the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface (control surface) is formed by connecting the particles at the exit and that is changed with time. The further assumptions and descriptions of this model have been shown in Chapters 2 and 4.

1.4.3 The method of NFPA for egress prediction [14]

There are several different approaches to calculate the egress time in super high-rise buildings. In this study, the calculation method to obtain the fundamental characteristics of crowd movement for egress prediction is mainly referring to the method of NFPA for egress prediction. The basic assumption is the population will use all exit facilities in the optimum balance; all occupants start at the same time [14]. This method provides the solution of “First order approximation” and more detailed analysis. More specifically, the estimating method of the flow capacity of a stair, flow capacity through a door, the speed of movement, and the building evacuation time is provided.

1.4.4 The experimental fire drills

Based on fire drills, a total of 229 participants and 7 cases of evacuation were performed in Taipei 101 and New Taipei City Hall which are about 508m and 140m tall, respectively. Within these cases, cases 1 to 6 were carried out in Taipei 101 and case 7 was carried out in New Taipei City Hall. The processes of the evacuations were recorded by the cameras and observers in the stairwells and the data were extracted out manually. The speed characteristics of occupants when evacuating down in the stairwells for various floor intervals have been presented and analyzed in Chapter 3. Some values of these data are used to be the egress parameters to analyze the effects of parameters on the mass evacuation in this study.

1.4.5 The algorithm of this study

In this study, the algorithm is shown as in Fig. 1-1. The research subject of this study is to analyze the mass evacuation in super high-rise buildings with control volume model. Firstly, the geometry, occupants, the size of stairs, and the function of different floors intervals of the building have to be determined. Then, the movement parameters of this study such as density, walking speed, stair flow, specific flow, etc. are estimated. The simulation process of evacuation modeling in the stairwell is divided into 5 stages and presented in Chapter 2.

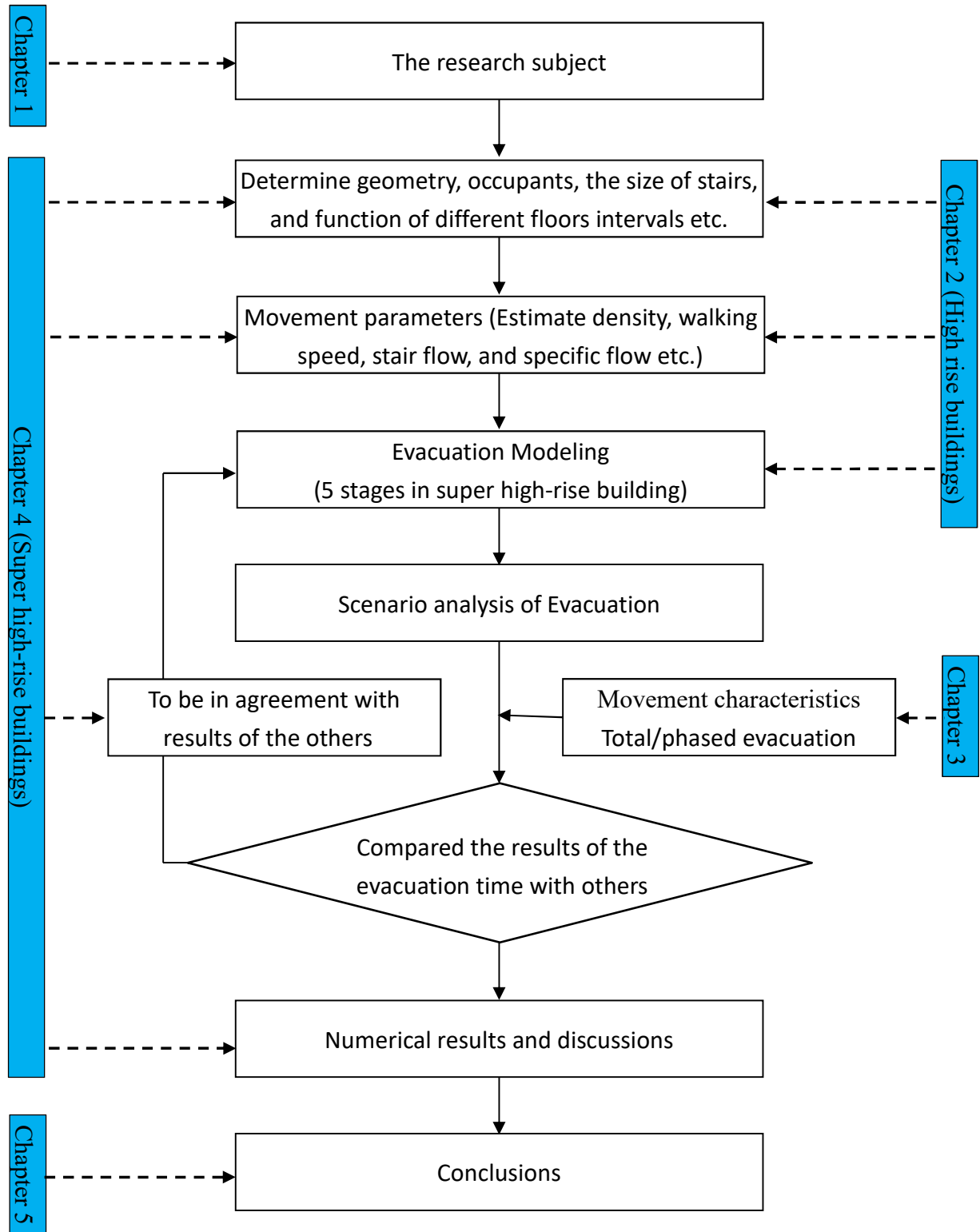


Fig. 1-1 The algorithm of this study

The results of evacuation time in this study agree well with the results of NFPA method [14] when using the same walking speed, dimensions of the floor, and coefficient of the occupant flow rate, which verified the rationality of the control

volume model in both modeling and execution aspects. Based on fire drills, Chapter 3 shows the speed characteristics of mass occupants in the stairwells for various floor intervals. In this study, Taipei 101, a super high-rise building is chosen for the object of evacuation simulation. Using the control volume, Chapter 4 provides the insights into the effects of different walking speed, coefficient of flow rate, and merge flow ratio on the dynamic change and the number of the occupants stagnating for each floor in various time scales. Finally, chapter 5 makes the conclusions of this study and offers some suggestions in the further works.

1.5 Literature Reviews

1.5.1 *Pre-movement time*

Many researches show that the first evacuation phase influences the evacuation procedure: this is called the pre-movement phase, which starts when the fire is detected and the occupants are alerted to evacuate. Purser and Bensilum [15] described a series of monitored evacuation studies and investigations of fire incidents in a range of different building types and discussed the strategies for the application of behavioural data to design standards and escape time calculation methods. They defined the pre-movement processes which began at an alarm or cue and when travel to an exit begins. There are two components [15]:

- (a) Recognition (this begins at an alarm or cue and ends with first response): during this phase occupants continue with pre-alarm activities (e.g. shopping, sitting, eating, watching football) and
- (b) Response (this begins at the first response and ends when travel to an exit begins): during this phase occupants carry out a range of activities (e.g. stopping machinery, securing money or other risks, gathering children and other family members, investigating the situation, wayfinding, altering others, fighting fire) [15].

In this phase, D'Orazio et al. [16] discussed that occupants took time trying to confirm any information announced about hazards, communicate with other individuals around them, collect their belongings, and wait for other people such as their friends or relatives in this phase. This study proposed a system (see Fig. 1-2) for reducing the pre-movement time that is based on an interaction with the people being evacuated. They investigated that people who use personal electronic devices (laptops, tablets) can be easily inclined to waste time in wrong behaviours in an emergency situation, such as saving data and packing up devices, which result in spending a lot of time on these activities. On the one hand, these activities lead to very high pre-movement time, thereby generating high individual total evacuation time [16].

The numerical characteristics dynamical features of this pre-movement phase have

been investigated for different buildings and circumstances, such as offices [17], stores [18], schools [19, 20], and theatres [21], etc. However, Liu and Lo [19] indicated that these numerical data showed wide distribution, depending on the type of building and activities in which people were engaged. They provided the results of whether the person took the evacuation as the first action as shown in Table 1-1. The most and secondly popular actions were “tidy up things” and “ignored”, rather than “evacuated” [19]. Recently, several studies have proposed the interactive methodologies for assisting evacuation in a real situation, and in particular, for pre-movement time reduction [22-24].

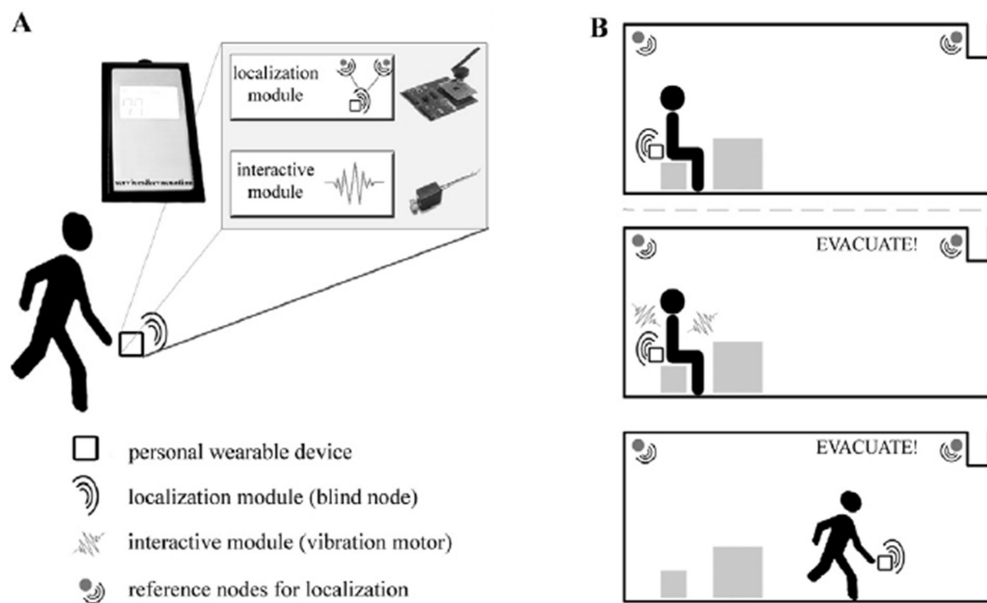


Fig. 1-2 Interactive wear system design: the composition of the system (A); a graphical representation of the three mail operating phases of this system (B) [16].

Table 1-1 Whether the person takes the evacuation as the first action [19].

	Frequency	Percentage
(a) Informed others	11	14.29%
(b) Telephoned other people	1	1.3%
(c) Dialed 999	1	1.3%
(d) Tidy up things	22	28.57%
(e) Attempted to extinguish the fire	1	1.3%
(f) Evacuated	11	14.29%
(g) Others	11	14.29%
(h) Ignored	19	24.68%

1.5.2 Merging behavior

In the staircase, merging occurs when the evacuees are descending from the upper floors and ones are entering the staircase at lower floor levels. This merging may have an impact on the escape time not only on the fire floor but also on the time for evacuating the entire building [25]. Several studies have been reported in the literature dealing with the observation of merging flows on stairs [26-30]. Hokugo et al. [26] studied the primary factor regarding the confluence of two traffic flows in the staircase and suggested that the merge ratios between stair and floor may be dependent upon which stream first established itself. Takeichi et al. [27] extended the earlier study of Hokugo et al. [26] to consider situations where the floor flow merges with the descending stair flow in two different locations, one adjacent to the incoming stair and one opposite to the incoming stair. The work of Hukugo et al. [26], Takeichi et al. [27] suggested that the merging behaviors at floor–stair interfaces are strongly influenced by physical attributes related to the architecture of the geometry and the density of the crowds on the stairs. Galea et al. [28] examined the representation of the merging process at the floor–stair interface within a comprehensive evacuation model. Numerical test case 1 involves a simple junction between two streams of flow which then continues in a single stream onto an exit. Numerical test case 2 is more representative of a floor–stair interface and represents a landing with dogleg stairs. One set of stairs approaches the merging landing from the floor above while another set of stairs continues from the merging landing to the landing below as shown in Fig. 1-3 [28]. A key practical finding of this analysis was that the speed at which a floor can be emptied onto a stair can be enhanced simply by connecting the floor to the landing at a location adjacent to the incoming stair rather than opposite the stair [28].

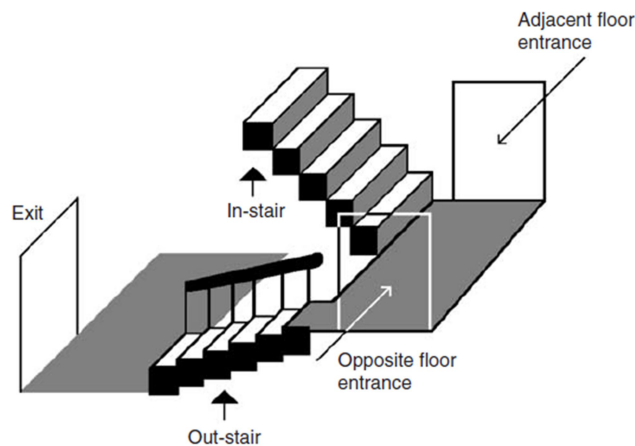


Fig. 1-3 Geometry for numerical test showing two alternative floor-stair interface regions on main landing [28].

Based on computer simulations, Ding et al. [29] investigated the merging behavior at the floor-stair interface of the high-rise building. Recently, Yajima et al. [30] investigated the characteristics of the walking and merging behaviors of occupants of a high-rise building descending to the staircase on the basis of observational data of a real total evacuation drill, and found that there was an approximate equal sharing of the merging process at the stair landing (i.e. proximately 50:50).

1.5.3 Evacuation simulation models

In order to analyze these phenomena, a number of theoretical models and numerical programmes have been established for studying the effect of human behaviors on the evacuation performance. The evacuation simulation models can generally be classified into two main categories: macroscopic and microscopic models [31, 32].

The macroscopic models consider the evacuees as an integer with the same characteristics so that the evacuation performance depends on the crowd flow velocity, crowd density, and physical factors of architectures. Regression model [33, 34], gas-kinetics model [35], queuing model [36], and Takahashi model [37], etc. are included in macroscopic category. In Ref. [34], the proposed methodology has three major contributions. First, a logistic regression model for guidance compliance behavior is calibrated using a virtual reality experiment and the critical factors for the behavior are identified. Second, the guidance compliance and following behaviors are considered. Third, benchmarks are calculated to evaluate the performance of optimized variable guidance, including the lower bound of the maximum evacuation time and the maximum evacuation time under a fixed guidance [34].

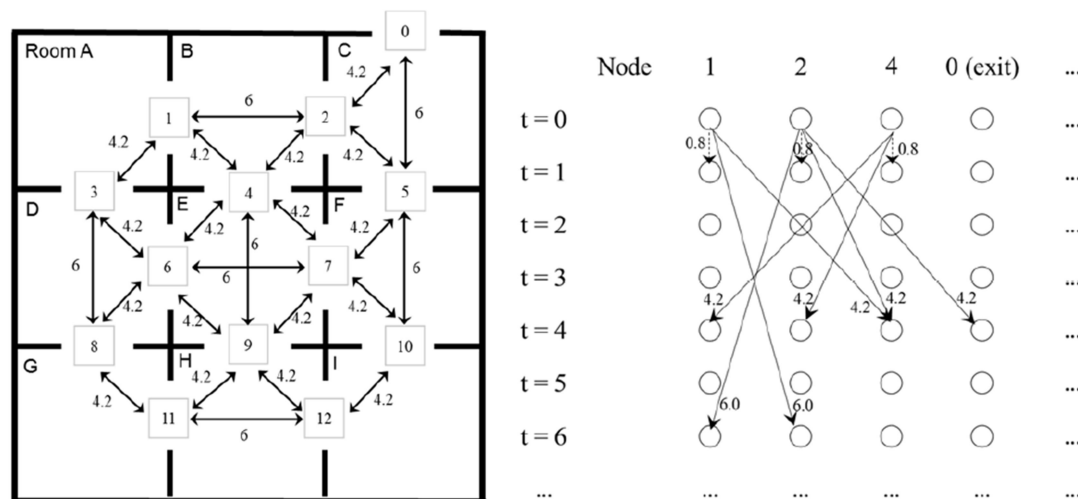


Fig. 1-4 Illustration of a sign network: on the left, the values on the links are the distance in the cell units and the travel time in time step units; on the right, a time-space network (The values next to the links are link costs. The solid lines are movement links. The dashed lines are waiting links.) [34].

The microscopic models not only consider the physical factors of architectures but also study the behavior and decisions of the individual evacuee and his interaction with the others in the crowd. Social forces [38-40], lattice gas (LG) [41, 42], integrated network approach [43], spatial-grid evacuation (SGEM) [44], multi-grid [45], hybrid space discretisation (HSD) [46], affordance-based finite state automata (FSA) [47], and cellular automata models [48-50] etc. are included in microscopic category. In addition, a number of microscopic model softwares with success applications for the analysis of building evacuation have been developed such as SIMULEX [51], EXITT [52], and building EXODUS [53, 54]. Generally, social forces, lattice gas (LG), spatial-grid evacuation (SGEM), multi-grid, hybrid space discretisation (HSD), affordance-based finite state automata (FSA), and cellular automata models are regarded as discrete models. They are discrete in space, time, and state variables.

For example, the general utility function of social forces model is formulated in Eq. (1) [40]. It is assumed that all random error terms are identically and independently standard Extreme Value Type I variables with the probability density function given in Eq. (2) [40]. The deterministic part of the utility is shown as Eq. (3), where β 's signify the utility coefficients (i.e. the marginal utilities) assumed to be distributed as independent normal random variables whose mean and standard deviations are to be estimated based on the data. The vector of all β 's is denoted as β [40].

$$U_{ni} = V_{ni} + \varepsilon_{ni} \quad (1)$$

$$f(\varepsilon_{ni}) = e^{-\varepsilon_{ni}} e^{-e^{-\varepsilon_{ni}}} \quad (2)$$

$$\begin{aligned} V_{ni} = & \beta_{1n}(\text{size of crowding near exit})_{ni} + \beta_{2n}(\text{distance to exit})_{ni} + \\ & \beta_{3n}(\underbrace{(\text{size of flows moving to exit})_{ni} \times (\text{exit visibility})_{ni}}_{=(\text{size of flows moving to visible exits})_{ni}}) + \\ & \beta_{4n}(\underbrace{(\text{size of flows moving to exit})_{ni} \times (1 - (\text{exit visibility})_{ni})}_{=(\text{size of flows moving to invisible exits})_{ni}}) + \\ & \beta_{5n}(\text{exit visibility})_{ni} \end{aligned} \quad (3)$$

In lattice gas model, the interactive forces (repulsive or attractive) are the key factors for a pedestrian in choosing the moving direction in the next time step. The effect of forces is in line with the principle of superposition, so the addition rule (vector superposition) is applied in Eq. (4) [42].

$$P_{i,j} = N I_{i,j} \delta_{i,j} (D_{i,j} + \sum_m f_{i,j}^m + \sum_W f_{i,j}^W) \quad (4)$$

where N is a normalization factor to ensure that $\sum_{(i,j)} P_{i,j} = 1$, $I_{i,j}$ is the inertia

factor of a pedestrian, and $D_{i,j}$ represents the strength with which a pedestrian rushes to the exit. Here, $\delta_{i,j} = 0$ if at least one pedestrian is in the lattice site at direction (i, j) and $\delta_{i,j} = 1$ otherwise. The term $\sum_m f_{i,j}^m$ denotes the interaction between pedestrians and $\sum_w f_{i,j}^w$ the effect from the surroundings (wall)[42].

Recently, Gasparotto et al. [55] developed an evacuation model based on a macroscopic continuous approach which overcame potential limitations of discrete models in terms of computational time, it consisted in the tracking of people density over time in a 2D domain. Nguyen et al. [56] presented an agent-based evacuation model with smoke effect and blind evacuation strategy (SEBES) which respects that recommendation by integrating a model of smoke diffusion and its effect on the evacuee's visibility, speed, and evacuation strategy. A review of literature related to identify the key behavioral factors, review the procedures and strategies, and analyze the capabilities of evacuation models of high-rise buildings was carried out by Ronchi and Nilsson [57].

1.5.4 Evacuation strategy planning

It is well known that proper evacuation strategy planning in high rise buildings will not only provide more safety escape paths and spaces for the occupants, but also minimize the evacuation times and casualties during emergencies. The strategy of evacuation of super high-rise buildings in Taiwan is essentially the phased evacuation down to the refuge/ground floor as instructed by PA-system using fire/smoke proof egress stairs. When coming to the refuge floor, occupants may transit from one staircase into another one. Considering the process of occupant evacuation in super high-rise buildings, the movement can basically be divided into three stages: (i), horizontal evacuation, which means occupants move to an exit on each floor; (ii), staircase evacuation, also known as vertical evacuation; and (iii), refuge floor transition, which means occupants will first move out of the staircase on to the refuge floor where they can choose to transit into another staircase or continue moving down by using an elevator [48].

For super high-rise buildings, the current evacuation strategies can basically be classified into two main subsets: phased evacuation and total building evacuation. In the phased evacuation, the occupants will be prioritized to evacuate firstly on the most hazardous floors like fire floor and the adjacent floors. The remaining occupants of the building will evacuate subsequently if necessary. In the total building evacuation, while the emergency fire is happening, all building occupants are expected to evacuate to the staircases which lead to the ground floor.

With the development of modern technologies, using the elevators in super high-rise buildings to assist total evacuation appears to be promising in improving

evacuation efficiency. Ma et al. [48] proposed a quantitative and viable elevator aided ultra-high rise building evacuation model which simulates both pedestrian movement and elevator transportation. They found that the interval design of refuge floors has a direct relation with the characteristics of the elevators and building occupants (see Fig. 1-5).

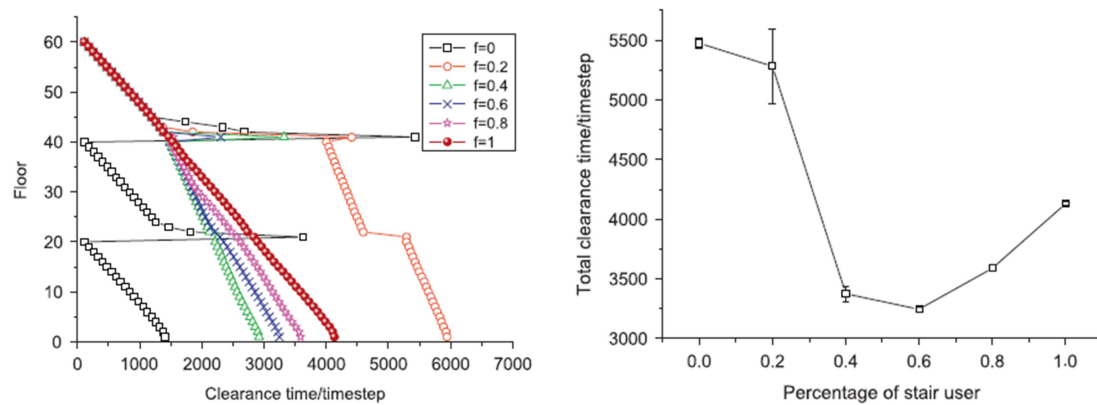


Fig. 1-5 On the left, clearance time in elevator aided total evacuation; on the right, accumulative outflow in total evacuation with different stair user percentages (The number of persons on a regular floor is 80, an elevator capacity is 15 persons) [48].

The studies of the potential availability of phased evacuation and the safe use of elevators strategy in fire evacuations have been conducted [58-60]. Koo et al. [58] presented new evacuation strategies for a heterogeneous population in high-rise building environments and compared them with traditional simultaneous evacuation strategy, and they found a vertically phased evacuation strategy that varies delay times by physical location was not useful for the simulated building.

Ronchi and Nilsson [59] investigated the use of egress models to assess the optimal strategy in the case of total evacuation in high-rise buildings. They employed a combined use of vertical (stairs and elevators) and horizontal egress components (transfer floors and sky-bridges) to investigate the effectiveness of different evacuation strategies for high-rise buildings. Based on computer modeling and simulation, the problem of evacuation strategies that utilize a combination of stairs and elevators for high rise buildings was investigated by Ding et al. [60]. The simulation results indicated that the optimal percentages of the occupants evacuated by the elevators, when achieving the shortest evacuation time, was almost not related to the number of evacuated persons and floors [61].

Using the building EXODUS, the performance of elevator evacuation in Taipei 101 was studied by Hsiung et al. [61], and Chien and Wen [62], they pointed out that elevator evacuation by the Taipei 101 can greatly shorten the evacuation time.

Applying the AnyLogic package, Liao et al. [63] developed an elevator evacuation model for ultra-tall building to explore which factors influence the elevator evacuation of an ultra-tall building. To quantitatively evaluate elevator assisted evacuation processes in ultra high-rise buildings, an event-driven agent-based modeling approach was proposed by Chen et al. [64].

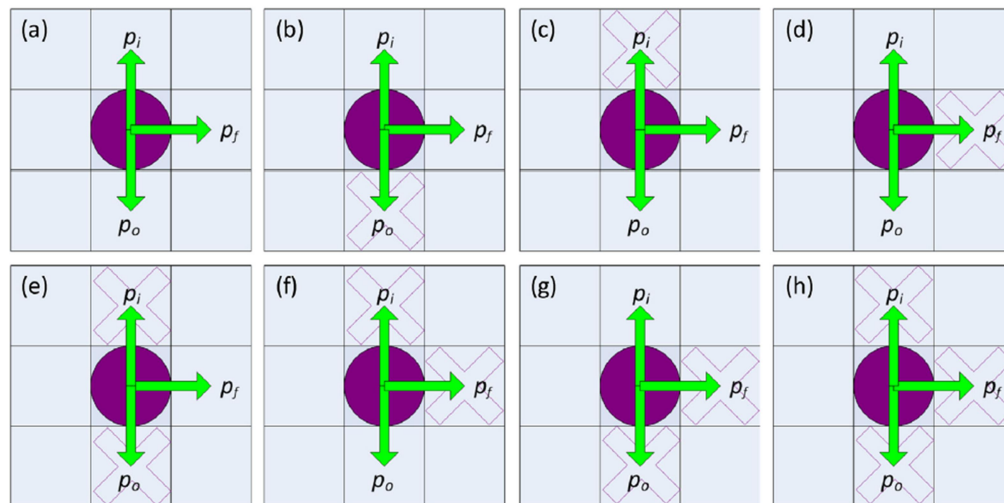


Fig. 1-6 Basic updates rules for evacuees [64].

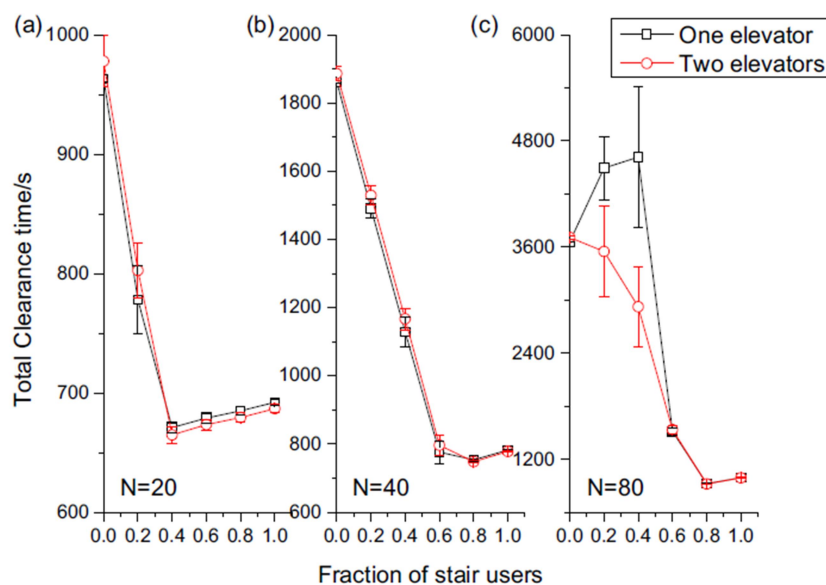


Fig. 1-7 Effect of fraction of stair user on total clearance time when one and two elevators for each refuge floor were used (The number of persons on a regular floor is 80 and the elevator capacity is 20 persons) [64].

The evacuees in the present study will move along different main directions in different regions. Given the main di-rection of movement as the forward movement direction, an occupant will encounter during the evacuation process as shown in Fig.

1-6 [64]. In this figure, p_f , p_i and p_o represents the probability of chosen the direction forward, inner/left side, and outer/right side, respectively, and it is assumed that, $p_f + p_i + p_o = 1$ [64]. It was found whether elevator egress will benefit evacuation or not has direct relation with the characteristics of the elevator, and sometimes, using elevators to move all occupants to ground safety point may not be an optimal solution (see Fig. 1-7). When elevator is allowed to assist building evacuation, its efficiency should be carefully examined by using the parameters including the elevator capacity, speed, acceleration and also jerk features [64].

1.5.5 Egress movement

However, if there are no proper managements of smoke control in super high rise buildings, the smoke that is generated during a fire will spread along gaps, ventilation ducts, corridors, stairways, and etc. On the other hand, modern communication links are very convenient and timely. When a fire occurs, occupants may have panic, making it difficult for occupants to obey the instructions of the phased evacuation, which can easily lead to the total evacuation. Furthermore, under the situations such as WTC 9/11, staying on the refuge floor might not be safe, which means occupants should move to the ground safety area and the total evacuation would be formed.

In reality, evacuation dynamics are significantly affected by the building geometries and the movement characteristics of the evacuating population, such as the presence of disabled occupants, counter flow, pre-movement delay, exit choice, and so on. Serious research into the evacuation of the functionally impaired and occupant characterization have been conducted by Boyce, Shields and Silcock [65-67]. Proulx [68] reviewed data sets on stairway movement that involves a complex set of behaviors, such as resting, investigation, and communication. Fahy [14] summarized and discussed the components of evacuation time and calculation methods for travel time, with their functions and relationships in the total concept of egress prediction of high-rise buildings. A database of travel speed and delay time data for various categories of occupants as well as the proportional of building users who reported difficulties in walking and using stairs have also been presented [14]. Peacock et al. [69] summarized the typical engineering variables used to describe stairwell movement during building evacuations. He also reviewed literature values for movement speeds and presented data from several new fire drill evacuations. This study [69] found that the mean movement speed of the 10-, 18-, 24-, and 31-story buildings evacuations was $0.48 \text{ m/s} \pm 0.16 \text{ m/s}$, with individual local movement speeds ranged from 0.056 m/s to 1.7 m/s , and used a distribution of movement speeds rather than a single value, which should provide more realistic representation of movement speed in stairwells.

An overall analysis of building safety and human behavior in fire has shown that psychonomics appear to have significant influence on occupants' fire response performances [70, 71]. The NIST study [72] combined the collection of new stair case movement data for elderly and mixed-ability occupants, and office populations, with a review of egress movement on staircases. These data collections are intended to provide a better understanding of this principal building egress feature and develop a technical foundation for future codes and standards requirements. Overall speeds varied from 0.07 m/s to 1.7 m/s with a mean of $0.44 \text{ m/s} \pm 0.19 \text{ m/s}$. The mean local speeds varied widely within and among stairs, ranging from $0.10 \text{ m/s} \pm 0.008 \text{ m/s}$ to $1.7 \text{ m/s} \pm 0.13 \text{ m/s}$. Thompson et al. [73] have highlighted the problems of an increasing proportion of elderly and obese people in society. They stated more research is needed to review existing knowledge of population demographics and crowd dynamics in order to derive an indicative flow reduction factor for future populations, and to consider the implications for computer models and building design in the future.

To quantify the flow features and validate the accuracy of the evacuation models, some of the experiment studies and drills regarded as phased evacuation and total evacuation were conducted in the stairwell of high-rise building [74-77]. Recently, Ma et al. [78] studied the evacuation of a single pedestrian to provide the data concerning ultra high-rise building evacuation from the 101st floor to the first floor in Shanghai World Financial Center, which is 470m tall. These data showed that the vertical moving speed of the evacuee was about 0.28 m/s; the mean speed of the evacuees along his/her movement direction was about 0.62 m/s. For the detailed analysis of the merging behavior, Boyce et al. [79] have investigated the merging flows and behaviors in stair landings through evacuation drills in three different buildings, and highlighted the potential influence of geometrical location of floor relative to the stair, relative door/stairs widths, and population characteristics on merge patterns. Wu et al. [80] investigated human movement characteristics in the stairwell of super high-rise buildings in Taipei 101 and New Taipei City Hall, which are about 508m and 140m tall, respectively. The results showed that the vertical speeds concentrated within in a range from 0.22~0.24 m/s and the walking speeds were within 0.61~0.65 m/s.

1.5.6 The control volume model

This control volume model has been applied to the evacuation time calculation in a high-rise/super high-rise building and the mass rapid transit (MRT) station by Wu et al. [11-13], and shown that the results of this model were quite reasonable. One of these basic assumptions of this model was adopted a hydraulic analogy which

evacuees were considered as a homogeneous fluid flow during the evacuation process.

In the previous study of the high-rise building [11] using the control volume model, the simulation had been carried out in a 9-story office building built by NFPA, a population of 300 persons/floor, and considered the total building evacuation. In this research, Taipei 101, a super high-rise building is chosen for the object of evacuation simulation. Not only the occupant's distributions are not uniform, but also there are the mechanical floors/refuge spaces on the floors interval. A number of parameters such as the exit flow rate, walking speed, coefficient of the exit flow rate, and merge flow ratio are taken into consideration in the continuous flow equation to calculate the total/phased building evacuation times and the number of people for each floor stagnating in time scales. Especially, the effect of mechanical floors on the evacuation process in Taipei 101 has been shown and discussed.

1.6 Conclusions of Chapter

Egress system, in concern with evacuation plans, human behaviors, and crowd management form the basis of good life safety design for emergency events [81]. Events such as the WTC 9/11 disaster and Grenfell Tower fire in June 2017 [82] have raised concerns and questions with regard to building codes and egress strategies used in the current situations.

This chapter provides the research background, research purposes, the methodology and algorithm of this study. The main aim of this study is to establish the evacuation modeling to investigate the numerical analysis of mass evacuation in a super high-rise building with the control volume model. To achieve this aim, literature reviewing, experimental drill data collecting, and scenario analysis of emergency evacuation modelling are applied. The algorithm of this study is presented as in Fig. 1-1.

The literature review involves collecting published articles related to the aspects of the evacuation process such as pre-movement time, merging behavior, evacuation model/method, human behavior, evacuation strategy planning in high-rise/super high-rise buildings.

The literature review shows that people who use personal electronic devices (laptops, tablets) can be easily inclined to waste time in wrong behaviours in an emergency situation which result in spending a lot of time on these activities [16]. On the one hand, the elevators in super high-rise buildings to assist total evacuation appear to be promising in improving evacuation efficiency. However, using elevators to move all occupants to ground safety point may not be an optimal solution [64].

The evacuation simulation models can generally be classified into two main categories: macroscopic and microscopic models. The macroscopic models consider

the evacuees as an integer with the same characteristics so that the evacuation performance depends on the crowd flow velocity, crowd density, and physical factors of architectures. The microscopic models not only consider the physical factors of architectures but also study the behavior and decisions of the individual evacuee and his interaction with the others in the crowd.

For egress movement in high-rise buildings, speeds varied from 0.07 m/s to 1.7 m/s with a mean of $0.44 \text{ m/s} \pm 0.19 \text{ m/s}$. The mean local speeds varied widely within and among stairs, ranging from $0.10 \text{ m/s} \pm 0.008 \text{ m/s}$ to $1.7 \text{ m/s} \pm 0.13 \text{ m/s}$ [72]. For super high-rise buildings, the vertical moving speed of the evacuee is about 0.28 m/s; the mean speed of the evacuees along his/her movement direction was about 0.62 m/s [80].

In recent years, improvements in computer technology have allowed a generation of computer models and new methods to simulate the processes of emergency evacuation in high-rise buildings. Whether the estimates are based on the data or calculations, means of egress and their design should be based on an evaluation of a building's total fire protection system and analysis of the population characteristics and hazards to the occupants of that building [83].

In this study, the control volume model assumes that each individual is an independent particle and a virtual closed surface that can be formed by connecting the waiting persons at exit. One of these basic assumptions of this model was adopted a hydraulic analogy which evacuees were considered as a homogeneous fluid flow during the evacuation process. The simulation process of evacuation modelling in the stairwell is divided into 5 stages and presented in Chapter 2. Based on fire drills, Chapter 3 shows the speed characteristics of mass occupants in the stairwells for various floor intervals. Chapter 4 provides the insights into the effects of different walking speed, coefficient of flow rate, and merge flow ratio on the dynamic change and the number of the occupants stagnating for each floor in various time scales. Finally, chapter 5 makes the conclusions of this study and offers some suggestions in the further works.

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Chapter 2

*Modeling the emergency evacuation of the high rise
building based on the control volume model*

Chapter 2: Modeling the emergency evacuation of the high rise building based on the control volume model

2.1 Introduction of chapter

The main aim of this chapter is to simulate the dynamics of the evacuees and derive the evacuation times of the high rise building by using the control volume model. The control volume model assumes that each individual is an independent particle and a virtual closed surface that can be formed by connecting the waiting persons at exit. This model had been successfully used to simulate the dynamic change of the evacuation occupants of the mass rapid transit station (see Appendix). In this chapter, the evacuation simulation process is divided into five stages and based on the assumptions of homogeneous flow with merge flow ratio where the exit flows from different floors meet and merge together. Seven scenarios are analyzed by using the various values of the parameters which influenced the evacuation process in the high rise building including walking speed, coefficient of flow rate and merge flow ratio. The simulation results are found to be in good agreement with the results of NFPA method. Furthermore, the dynamic characteristics of the evacuation process at each time-step for each of the floors are presented and discussed.

2.2 The assumptions in modeling high-rise building evacuation

2.2.1 Basic assumptions

In this chapter, the control volume model theory is considered as a basis and referred to NFPA [1] in the algorithm of evacuation time calculation. The physical assumptions of the control volume have been defined by Wu et al.[2, 3]. When the occupants in the floor escape, they flow out from the rooms and tend to stagnate near the exit of the floor as shown in Fig.2-1.

During evacuation process, when the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface (control surface) is formed by connecting the particles at the exit and that is changed with time. By setting the height of the particle (each individual) as 1, the area of the closed surface is equal to the control volume. Assuming the particle number per unit area as a constant, the transient area of the control volume can be easily derived from particle number within the control volume. The further assumptions of this model are shown as following:

- (1) During evacuation the evacuee flow is homogeneous, which means the evacuee walks with the same velocity, the evacuee flow from door or exit is continuous, the specific flow is a constant, and all occupants start egress at the same time.

- (2) When stagnation occurs, the number of the occupants per unit area remains a constant.
- (3) In each floor, the merge flow ratio of the descending stair entry flow and exit flow is a constant.
- (4) The pre-movement time –lag, alarming response, and broad casting response are not considered.
- (5) The occupant reaching the ground floor is considered a successful escape.

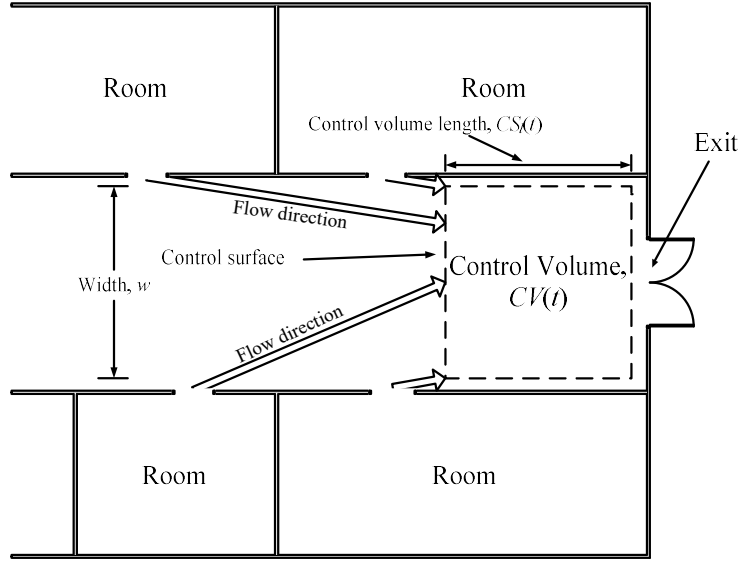


Fig. 2-1 The control volume model of the floor evacuation.

The total number of occupants flowing to the control volume at certain time point t can be presented by Wu et al. [2, 3] as follows:

$$Q_{total}(t) = \sum_{n=1}^M (\dot{Q}_n(t) \times t) + TR - \dot{Q}_{out} \times t \quad (2-1)$$

where $\dot{Q}_n(t)$ is the flow rate of the occupants at the n th exit moving to the control volume (people/s), TR is the original number of occupants on the floor (people), t is the time scale (sec), and \dot{Q}_{out} is the flow rate of the occupants moving toward the exit (people/s). Because the number of occupants per unit area is a constant, the size of the control volume at certain time point t can be formulated as $CV(t) = Q_{total}(t) / PA$ where $CV(t)$ is the value of the control volume at certain time point t (m^2), PA is the number of occupants accommodated per unit area (people/ m^2).

The length $CS_l(t)$ of the control volume at certain time point t can be derived as:

$$CS_l(t) = CV(t) / w \quad (2-2)$$

where w is the effective width of the corridor (m). It is worth mentioning that the effective width of the corridor is not equal to its actual width as passengers tend to flock around the exits.

2.2.2 Scenario analysis of emergency evacuation

The emergency evacuation is divided into five stages where stage 1 is the occupants departing from the room and arriving at the floor exit; stage 2 is the occupants descending to the next floor; stage 3 is the occupants of the $n+1$ th floor merging with the crowd originally occupying the n th floor; stage 4 is the combined crowd reaching the maximum capacity of the stairwell; stage 5 is the completion of the evacuation.

The calculation means of evacuation time for each stage are described as following:
 (1) Stage 1: the occupants evacuate the rooms and arrive at the exit of the floor as shown in Fig. 2-2. The evacuation time is obtained by dividing the distance between the floor exit and the nearest room exit by the walking speed.

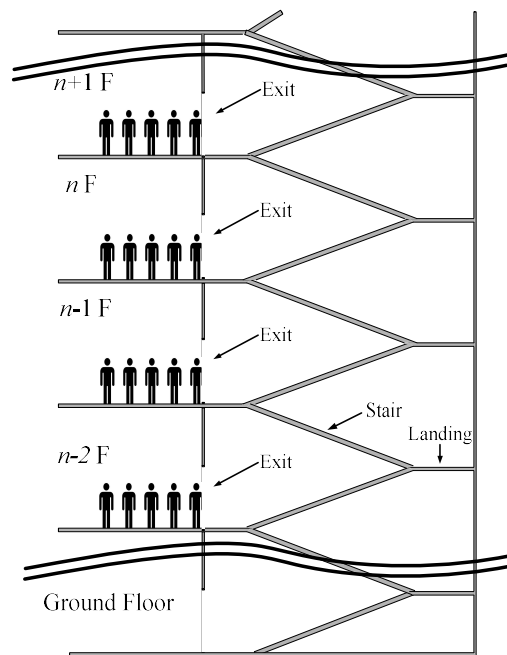


Fig. 2-2 Stage 1: The occupants flow to the exit.

(2) Stage 2: the exit flow enters the stairwell and the stagnation occurs at the floor exit when the summed flow rates of all room exits in a single floor exceed the flow rate of that floor exit. The evacuation time is not measured until the occupants descended to the next floor (shown as in Fig. 2-3).

(3) Stage 3: when the stair entry flow arrives at the lower floor and meets with the sources of exiting occupants as shown in Fig.2-4, it is called “merge flow” (i.e. merge

stage). This stage is assumed that the summed merge flow capacity of the $n+1$ th floor's stair flow and the n th floor's exit flow is larger than the maximum stair capacity. The merge flow ratio R can be calculated as follows:

$$R = \dot{Q}_{n,s} / \dot{Q}_{n,e} \quad (2-3)$$

where $\dot{Q}_{n,s}$ (people/s) is stair flow of the $n+1$ th floor moving downward to the n th floor, and $\dot{Q}_{n,e}$ (people/s) is the exit flow of the n th floor.

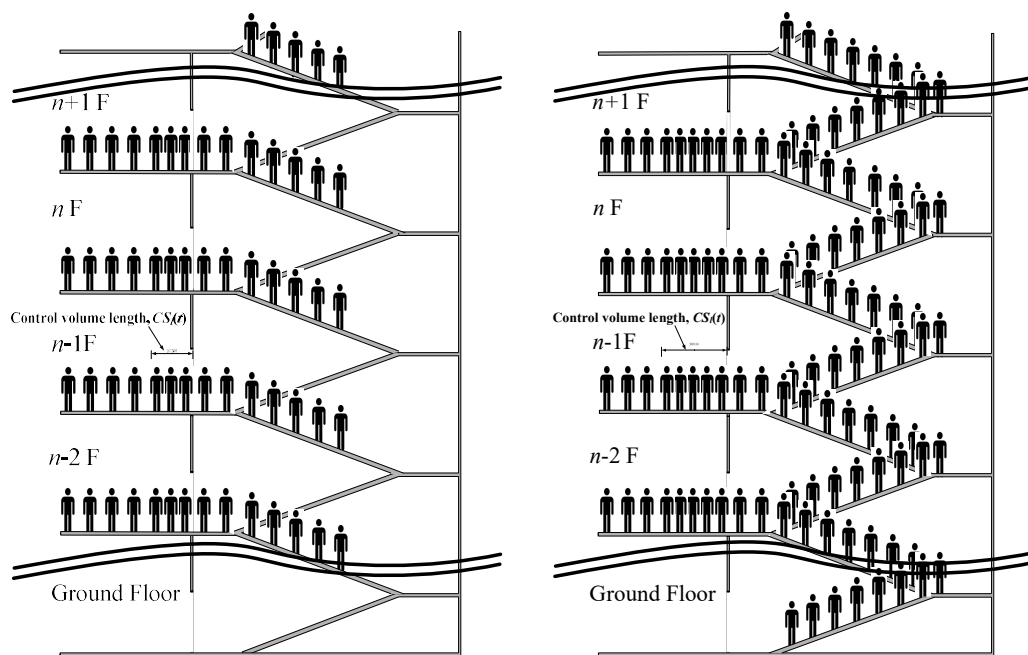


Fig. 2-3 Stage 2: The occupants move downward to lower floor.

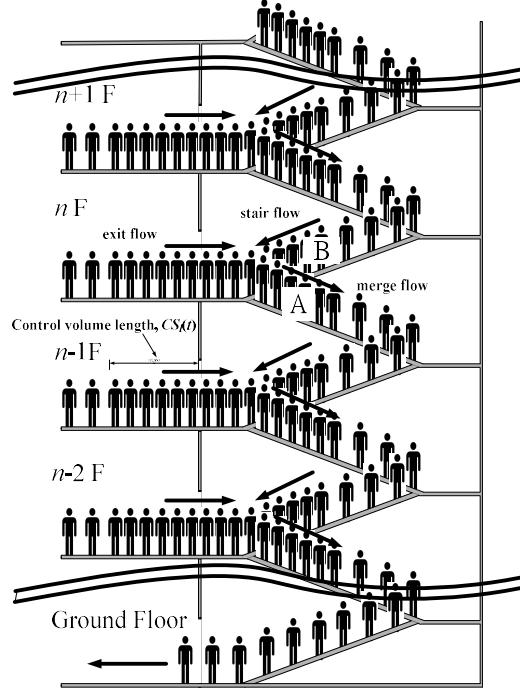


Fig. 2-4 Stage 3: merge stage.

When the descending flow (as mark **A** in Fig. 2-4) reaches the maximum stair capacity, the stagnation occurs (as mark **B** in Fig. 2-4) where two groups of the occupants' merge. In this stage, the maximum value of the stair flow capacity is denoted as $\dot{Q}_{s(\max)}$ and the exit flow of the n th floor, $\dot{Q}_{n,e}$, can be calculated as follows.

$$\dot{Q}_{n,e} = \frac{\dot{Q}_{s(\max)}}{R+1} \quad (2-4)$$

(4) Stage 4: the simulation entered stage 4 when the number of the occupants of a single floor approaches the floor capacity as shown in Fig. 2-5. The maximum number of the occupants a floor can be obtained by two components: stair landing area (m^2) multiplied by maximum crowd density of the stair landing (people/m^2), and stairwell area (m^2) multiplied by maximum crowd density of the stairwell (people/m^2). The descending flow is consisted of both stair entry flow and the outflow of the floor.

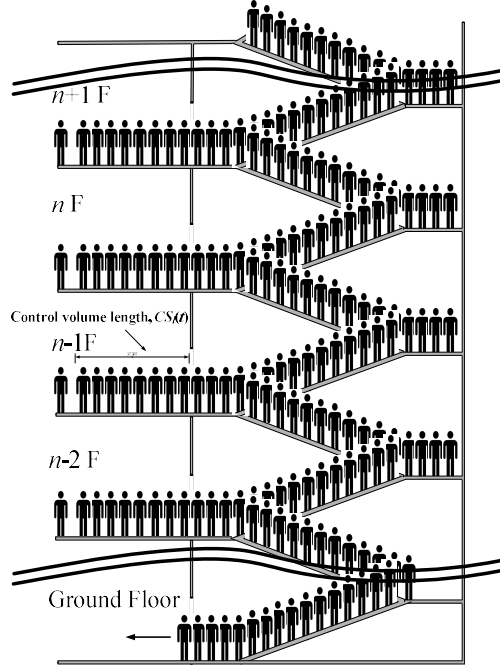


Fig. 2-5 Stage 4: the number of the stagnating occupants reached the maximum.

When the occupants fully load the stairwell, the stair entry flow between ground floor and second floor will keep the maximum stair flow. It should be noted that though the merge flow ratio of the descending stair entry flow and exit flow for each floor is a constant, the value of stair entry flow and exit flow will vary with for different floors. In this stage, the relationship between the merge flow ratio (R), the stair entry flow of the n^{th} floor ($\dot{Q}_{n,s}$) and exit flow ($\dot{Q}_{n,e}$) is described as follows.

$$\dot{Q}_{n,s} = \dot{Q}_{s(\max)} \times \left(\frac{R}{R+1}\right)^{n-1} \quad (2-5)$$

$$\dot{Q}_{n,e} = \dot{Q}_{n,s} \times \frac{1}{R} \quad (2-6)$$

(5) Stage 5: formula 5 and 6 demonstrate that the higher the floor the smaller the flow rate of the floor when the value of the merge flow ratio is lower than a certain constant and the number of the stagnating occupants in the stairwell reaches the maximum. As a result, the occupants on the second floor take the lead in arriving at the ground floor and yet finish the escape behind others as shown in Figs. 2-6. On the contrary, when the value of the merge flow ratio exceeds a certain constant, the occupants of the roof floor take the lead in entering the stairwell.

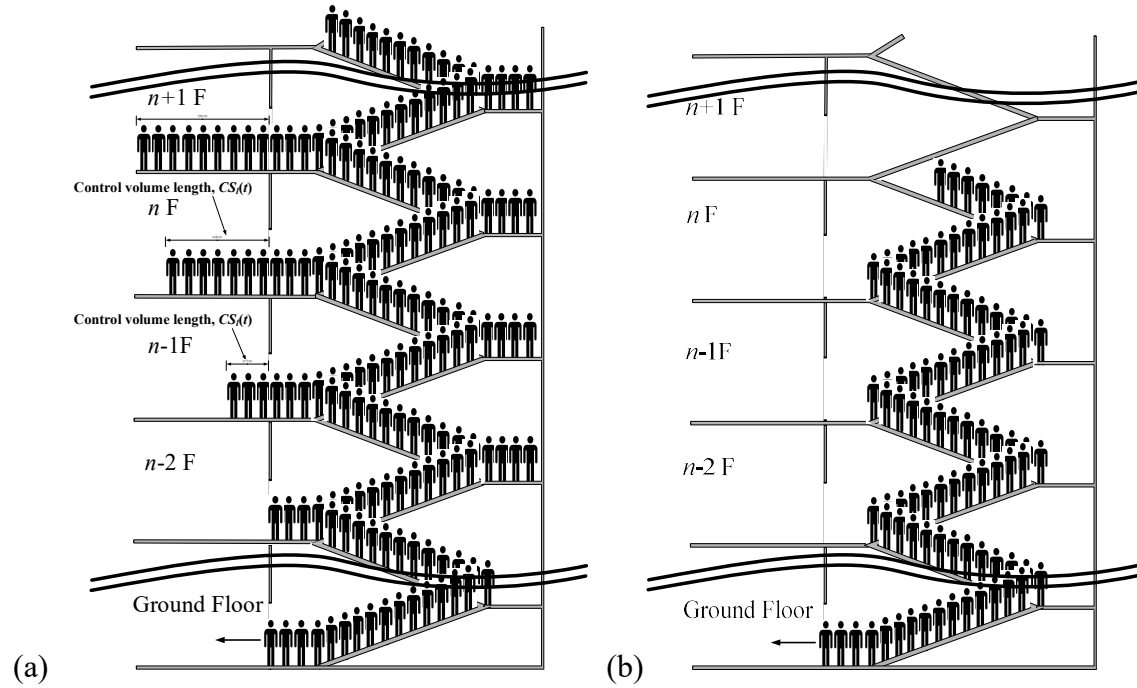


Fig. 2-6 Stage 5: the case for smaller merge flow ratio (a); evacuation completed (b).

2.3 Modeling and analysis

2.3.1 The simulation model

In order to compare with the results derived from this model, the simulation has been carried out in a 9-story office building built by NFPA [1] as shown in Fig. 2-7. There are 10 office partitions in each floor and the dimensions of the floor are 3.6576 m(12 ft), 91.44 m(300 ft) and 24.384 m(80 ft) in height, length, and width, respectively. There is one 0.914 m(36 in.) clear width door at each stairway entrance and exit. Each stair is 1.118 m(44 in.) wide (tread width) with handrails protruding 0.006 m(2.5 in.) In this chapter, the effective widths of the exit, the stair and the corridor are 0.610 m, 0.813 m, and 2.134 m, respectively. There equipped with one indoor safety stair at both wings of the building and there is a population of 300 persons/floor. There are two $2.975 \text{ m}^2 (=4 \text{ ft} \times 8 \text{ ft})$ landings per floor of stairway travel. The total population of 2400 persons above the first floor will evacuate through the stairwell. The parameters of this model are listed in Table 2-1 and Fig. 2-8.

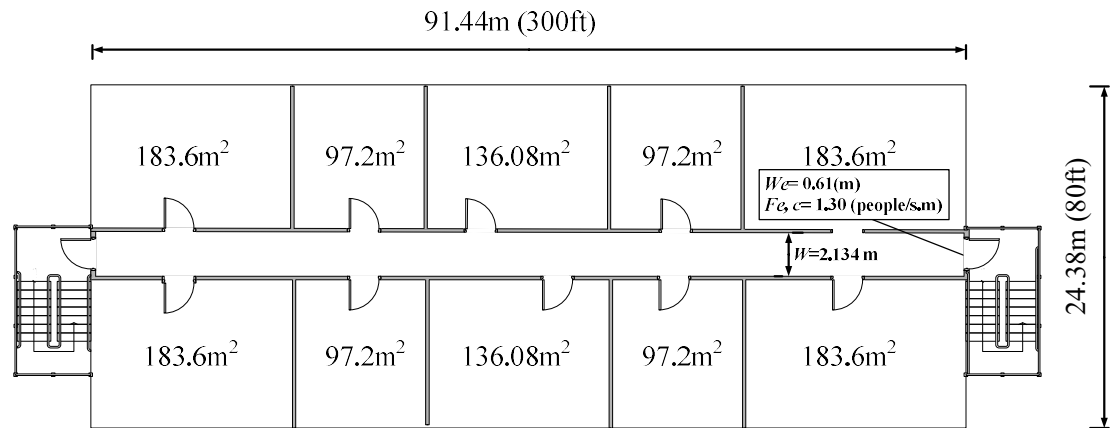


Fig. 2-7 Floor plan of the model simulation.

Table 2-1 The parameters of the model.

Exit route element	Parameter
Floor to floor height	3.66 m(= 12ft)
Stair riser	17.8 cm(=7.0 in.)
Stair tread	27.9 cm(=11.0 in.)
Effective width of the exit (We)	0.610 m
Effective width of the stair (Ws)	0.813 m
Effective width of the corridor	2.134 m
Landing area	2.98 m ² (= 4 ft × 8 ft)
The exit specific flow ($F_{e,c}$)	1.30 pers/s.m
The stair specific flow ($F_{s,c}$)	1.01 pers/s.m
The maximum capacity of the stair	11 persons
The maximum capacity of the landing	36 persons

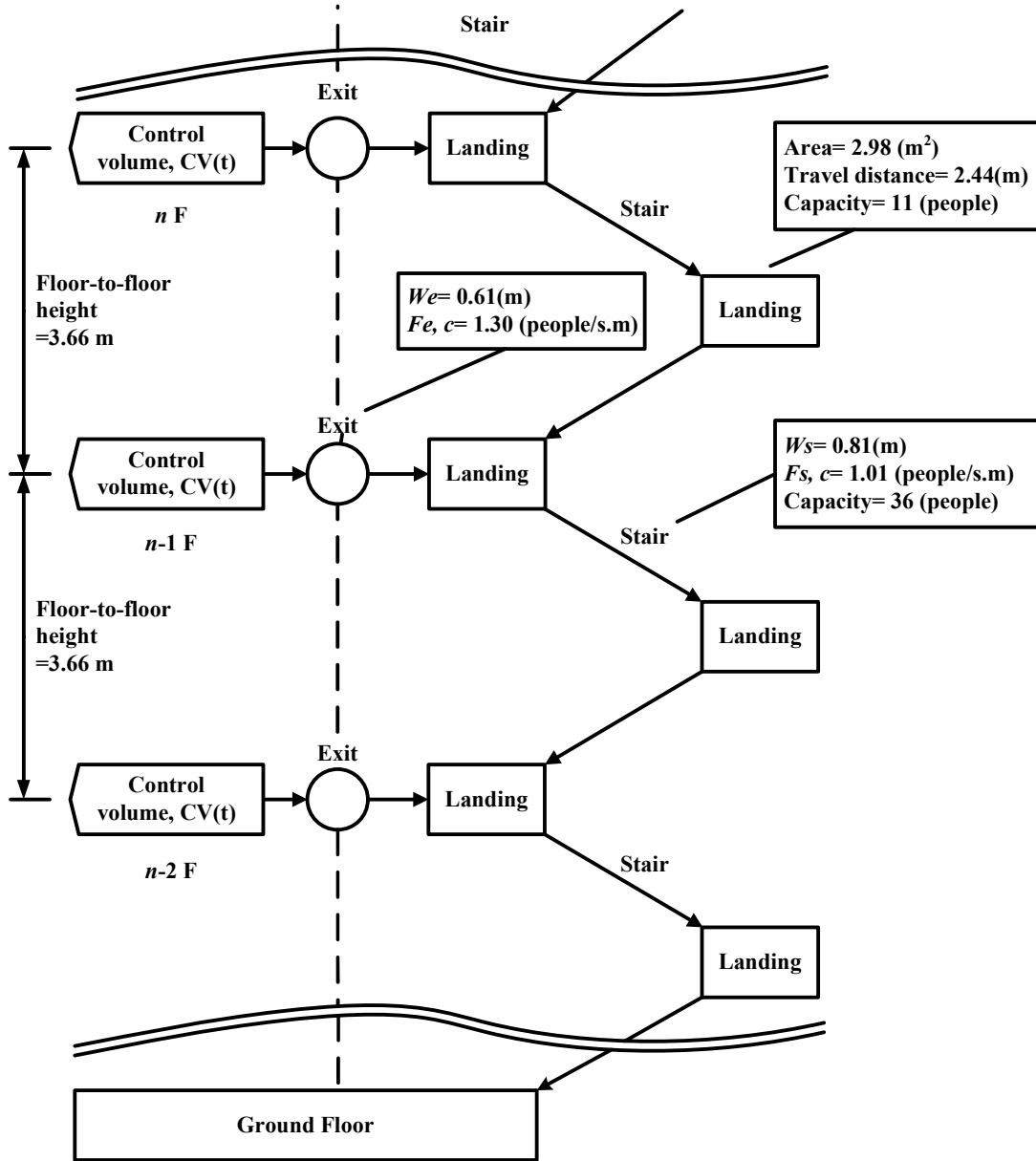


Fig. 2-8 Flow diagram of the control volume model.

The specific flow (F_c) is in people/s.m when density is in people/m² and speed is in m/sec. In this chapter, the exit specific flow ($F_{e,c}$) is 1.30 people/s.m and the stair specific flow ($F_{s,c}$) is 1.01 people/s.m. The maximum capacities of the stair and the landing are 11 persons and 39 persons, respectively. It is assumed that the occupants are evenly allocated to the indoor safety stairs at both wings, which indicated the number of the occupants at each wing is equal. It should be noted that the actual calculated flows at the initial stage for exit and stair are $F_{e,c} \times W_e$ and $F_{s,c} \times W_s$, respectively.

2.3.2 Scenario analysis

In this chapter, seven scenarios are presented as in Table 2-2. In case 1, 2, 3, and 4, the parameters of walking speeds and specific flow are the same as NFPA adopted. For the simulations of NFPA calculation, the higher floors are fully evacuated prior to the lower floors and thus the occupants of the lowest floor escape to the safety area at last. The scenario and consequent parameter values in the control volume theory are similar to those of NFPA when R is equal to 100 i.e. case 1 is considered.

Table 2-2 The occupant behavioral parameters in the control volume model.

Scenarios	Merge ratio(R)	Speed $v(m/s)$	Specific flow ($p/s.m$)	Descriptions
case1	$R=100$	$v_e=1.19$	$F_{e,c}=1.30$	The parameters of walking speeds and specific flow are the same as NFPA [1]
case 2	$R=1.0$	$v_s=0.95$	$F_{s,c}=1.01$	
case 3	$R=10$			
case 4	$R=0.1$			
case 5	$R=1.0$	$v_e=1.30$ $v_s=0.783$	$F_{e,c}=1.30$ $F_{s,c}=1.01$	The parameters of walking speeds are the same as Building Center of Japan [4].
case 6	$R=1.0$	$v_e=1.32$ $v_s=0.66$	$F_{e,c}=1.30$ $F_{s,c}=1.01$	The parameters of walking speeds are the same as SIMULEX [5].
case 7	$R=1.0$	$v_e=1.19$ $v_s=0.95$	$F_{e,c}=1.12$ $F_{s,c}=0.767$	The parameters of specific flow are the same as Wu et. al. [2].

It is well known that the exit flow is changed with the merge flow ratio during merge stage when the number of the occupants stagnating in the stairwells reaches the highest value. In addition, it is an empirical fact that the flow or its velocity decreases when there are people squeezing through the descending crowd. However, it is difficult to investigate the real-world merge flow ratio distribution as a large number of factors influence the evacuation and change in time scale including the physical capabilities and psychological conditions of the occupants, the development situation of the fire, and the surrounding of the architectures. Therefore, one of the main aims of this chapter is to analyze the different merge flow ratios and simulate the various

evacuation processes.

Except for $R = 100$ in case 1, 1.0, 10 and 0.1 are used for the merge flow ratio in case 2, 3, and 4, respectively. When R is equal to 1, the walking speed values of Japan Building Center [4] are assigned to case 5, those of SIMULEX [5] are used in case 6 and those of Wu et al. [2] are set in case 7.

2.4 Numerical results and discussions

Using control volume model with different walking speeds, coefficients of flow rate and merge flow ratios, the results of simulations are obtained. In this chapter, the simulation results of the control volume model are compared with those which were presented in NFPA [1]. The evacuation time and the number of people stagnating versus time in each floor are shown and discussion as following.

2.4.1 Comparison of the evacuation time of the control volume model and NFPA

It is a mean of NFPA evacuation calculation that the occupants of the roof floor have the priority over those of other floors to be evacuated. The occupants of the lower floors do not start making their escape until those of the higher floors complete evacuation. It should be noted that if all of the occupants in the building start evacuation at the same time, each stairway can flow out 49 people/min. An addition 0.36 minute travel time is required for the movement from the second floor to exit. The minimum evacuation time for this model is estimated at 25.4 minutes.

In case 1 in which R is equal to 100, i.e. the stair flow rate is far higher than the exit flow rate as shown in Fig. 2-9 and Table 2-3, the occupants of the 9th floor are the first ones to complete evacuation (198 sec) and the occupants of the 2nd floor are the last ones (1512 sec). In Table 2-3, the control volume model to be in good agreement with NFPA calculation in terms of the time required for complete evacuation for each floor. Therefore, the analytical method in this chapter is reasonable.

Table 2-3 Comparison of the evacuation time between the control volume model and NFPA.

Evacuation	Time (min)	
	Present (case 1, $R=100$)	NFPA (2008)
All persons have evacuated the 9 th floor	198 sec (3.3 min)	218 sec (3.6 min)
All persons have evacuated the 8 th floor	380 sec (6.3 min)	401 sec (6.7 min)
All persons have evacuated the 7 th floor	569 sec (9.5 min)	584 sec (9.7 min)

All persons have evacuated the 6 th floor	758 sec (12.6 min)	767 sec (12.8 min)
All persons have evacuated the 5 th floor	947 sec (15.8 min)	950 sec (15.8 min)
All persons have evacuated the 4 th floor	1136 sec (18.9 min)	1133 sec (18.9 min)
All persons have evacuated the 3 rd floor	1324 sec (22.1 min)	1316 sec (21.9 min)
All persons have evacuated the 2 nd floor	1512 sec (25.2 min)	1499 sec (25.0 min)
All persons have evacuated the building	1535 sec (25.6 min)	1518 sec (25.3 min)

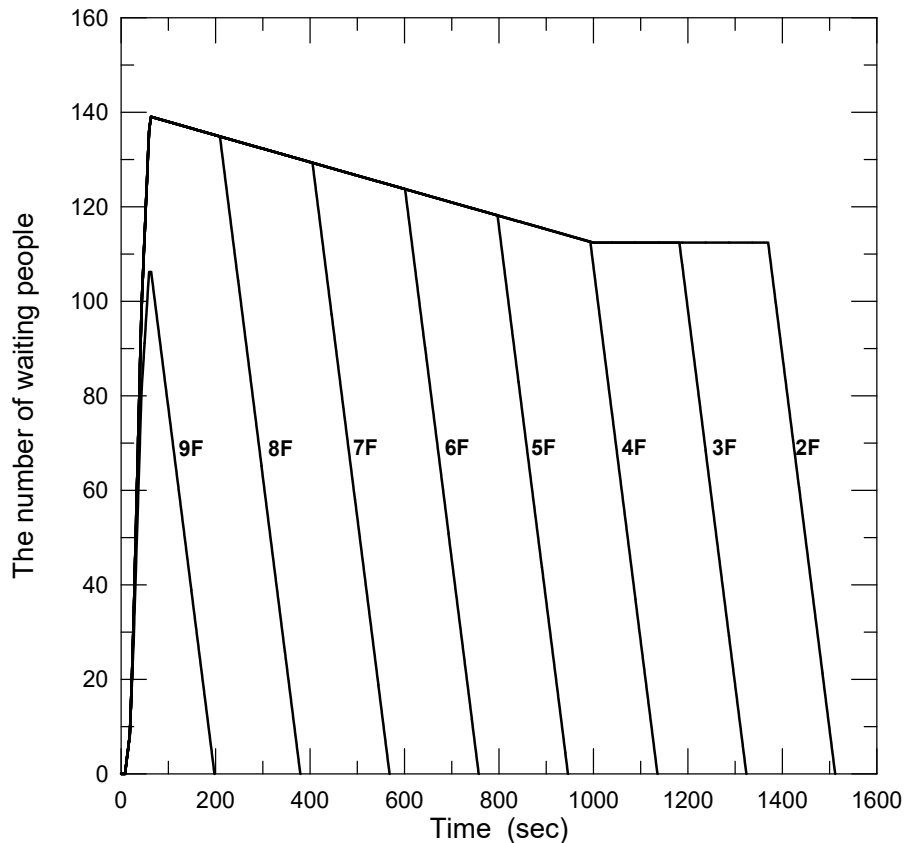


Fig. 2-9 The simulation results of the control volume model (case 1, $R = 100$).

2.4.2 Effect of different merge flow ratios

Because a certain proportion of the evacuees enter the stairwell beneath during the merge stage, the effect of different merge flow ratios on simulation should be considered. Fig. 2-10 shows the results of the case 2 ($R=1.0$). The stair entry flow merges with the exit flow at 21 sec (stage 3) when the exit flow decreases and thus the increase of the stagnated occupants in the floor is accelerated (as mark **a** in Fig. 2-10). At 64 sec in the time scale, the number of the occupants stagnating in the 2nd floor exit peaked – an approximation of 124 people at stage 4. The number of the occupants in the control volume decreased in proportion to the outflow of the merge crowd in the 2nd floor (as mark **b** in Fig. 2-10). The exit flow rates of the other floors are dominated

by the merge flow ratio. The higher the floor, the lower its exit flow rate is. As a result, the occupants of 2nd floor are the first to be evacuated and all its occupants enter the stairwell the soonest. In the meanwhile, the stairwell between the 2nd and 3rd floor remains congested until the occupants gradually flow to the ground floor. Followed by the clearing of the stairwell, the exit flow of the 3rd floor is increased and so on.

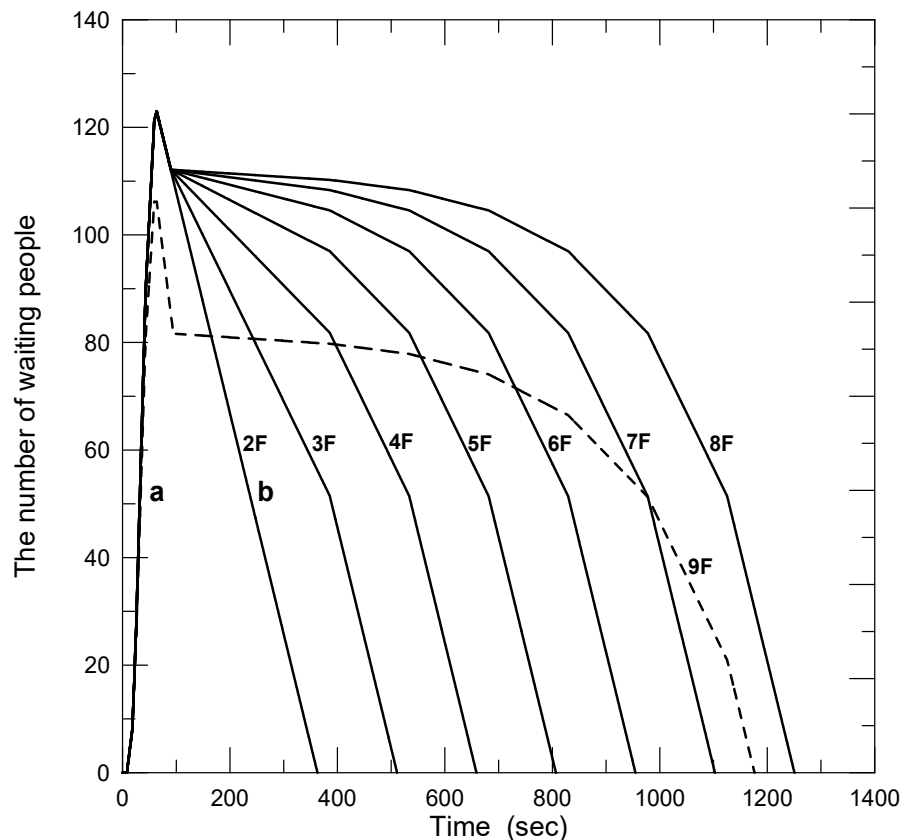


Fig. 2-10 The simulation results of the control volume model (case 2, $R=1.0$).

It is concluded from the above mentioned $R=1.0$ simulation that the 2nd floor is the first to be fully evacuated in spite of the limitation of maximum stair flow when the stair flow rate and the exit flow rate is the same. The higher the storey, the lower its flow rate is. It is worth mentioning that the evacuees of the 9th floor enter the stairwell earlier than those of the 8th floor because there is no merge happening in the roof floor, which does not lead them to quicker arrival at the ground floor.

Now one considers the merge flow ratio of the stair flow rate to the exit flow rate is 10 (case 3), the results of simulation are shown in Fig.2-11. The figure shows that the simulation results are similar to case 1 i.e. the 9th floor is the first evacuated to pass through the exit (199 sec) and 2nd floor is the last (1490 sec). The highest value of the waiting people is 137 at 72 sec in the 2nd floor.

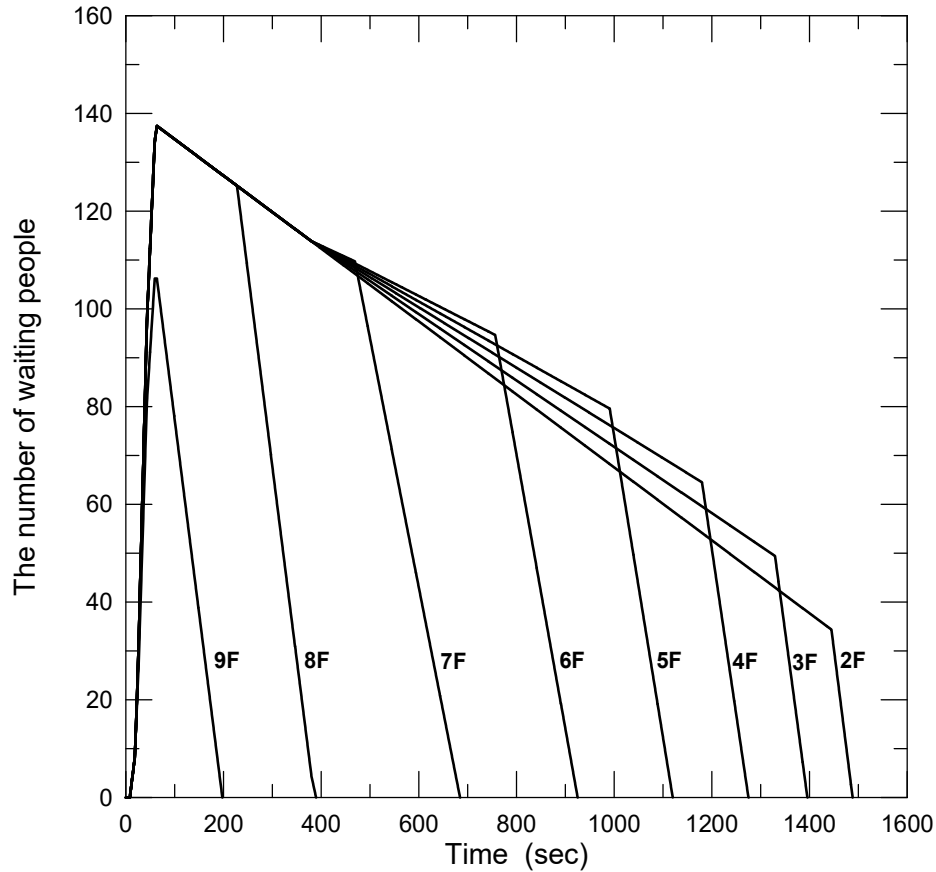


Fig. 2-11 The simulation results of the control volume model (case 3, $R=10$).

Fig. 2-12 shows the effect of the small value of merge ratio on evacuation processes. When $R=0.1$ (case 4), most evacuees of other floors remained waiting before 2nd floor is evacuated (209 sec). As only few evacuees of the higher floors flow to the lower floors, the 9th floor is last floor to enter the stairwell (1295 sec).

In this chapter, the results show the time needed to evacuate for different floors, how numbers of the evacuees stagnating, and what happens in each floor at different merge flow ratio levels in various time scales. Although the evacuate time in cases 1, 2, 3, and 4 does not deviate much, it is noted that each floor is different in terms of the number of the evacuees stagnating and entering the stairwell and time scale. For example, the total evacuation time for case 1 and 4 is different by only 60 seconds. However, the time that the 9th floor evacuees took to enter the stairwell is 198 seconds for case 1 and 1295 seconds for case 4. Similar phenomenon could be found in different floors.

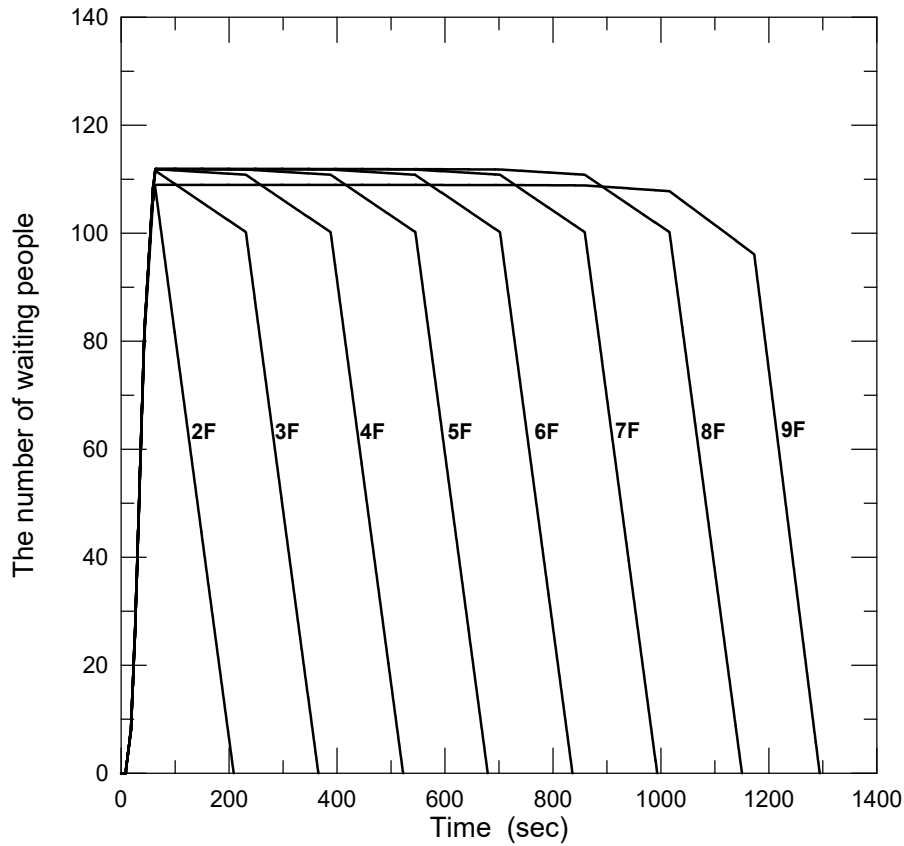


Fig. 2-12 The simulation results of the control volume model (case 4, $R=0.1$).

2.4.3 Effect of different walking speeds

In order to understand how walking speed would affect the simulation results when R is equal to 1, the walking speed values of Japan Building Center [4] are assigned to case 5 and those of SIMULEX [5] are used in case 6. The results are compared and plotted in Figs. 2-13 and 2-14, respectively. It is assumed that velocity V_e/V_s would determine the evacuation time when the values of the specific flow are identical. However, it is found that when there is stagnation in every floor, velocity of walking did not create much advantage in shortening the evacuation time. The evacuation times differ within the range of only 0.2 minute (12 seconds) across 2F, 4F, 6F, 8F, and 9F in case 2, 5 and 6.

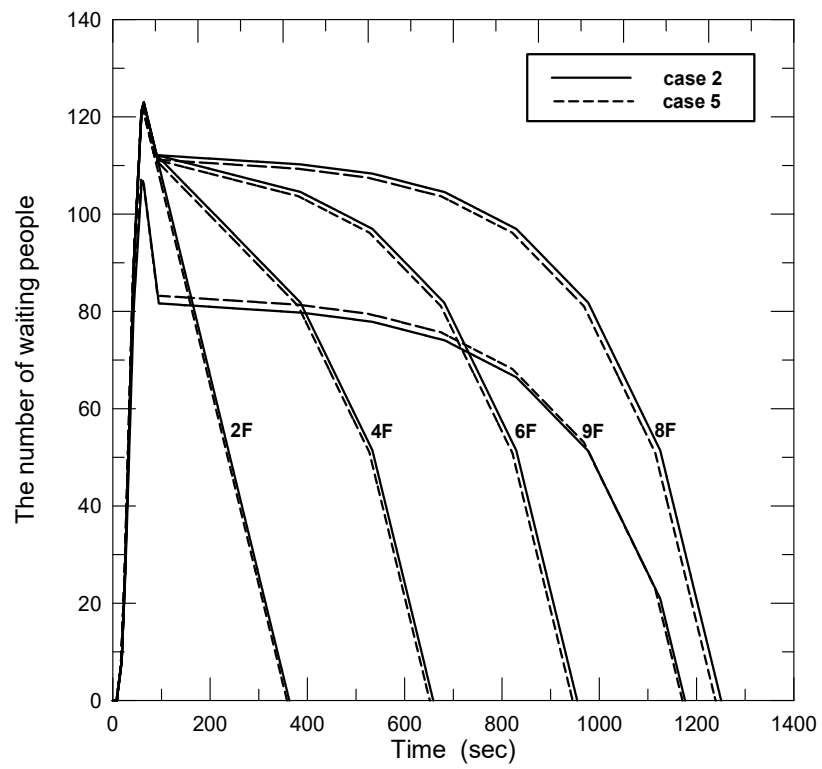


Fig. 2-13 The simulation results of case 2 and case 5.

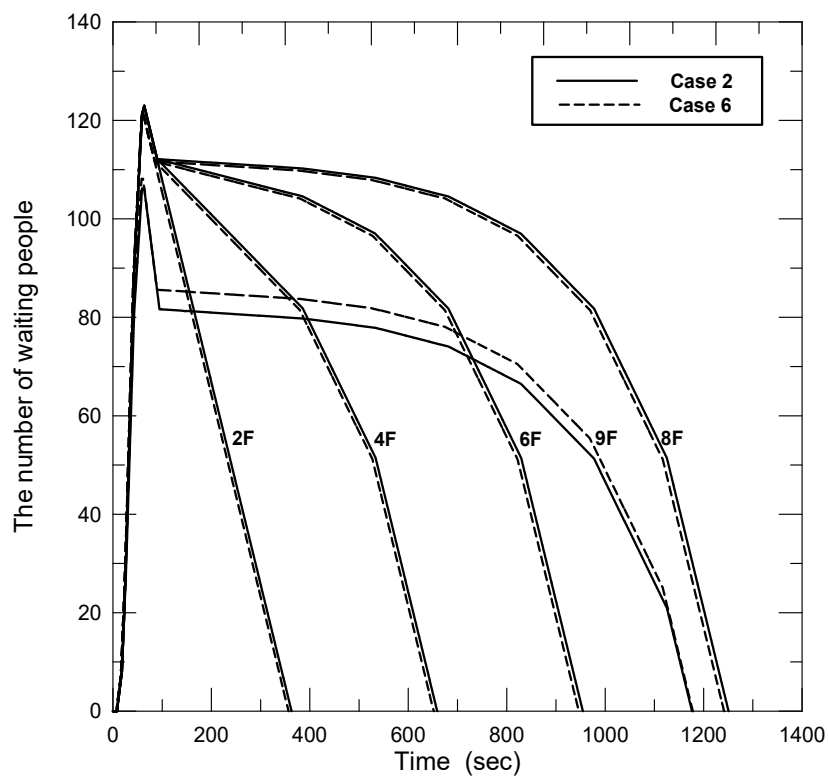


Fig. 2-14 The simulation results of case 2 and case 6.

Using the office staff as the evacuee, Table 2-4 shows that the results of the evacuation time obtained from the control volume model and SIMULEX software. From this table, it is well known that the required evacuation time of SIMULEX for each floor is shorter than that of control volume. The difference of evacuation time to ground floor for these two models is 341 seconds. It should be noted that the dimensions of the exit, the stair and the corridor built in SIMULEX are 0.914 m, 1.118 m, and 2.438 m, respectively. However, the effective widths of the exit, the stair and the corridor used in the control model are 0.610 m, 0.813 m, and 2.134 m, respectively. Moreover, these two methods have the same phenomenon of the evacuation performance that the evacuees of the 9th floor enter the stairway earlier than those of the 8th floor.

Table 2-4 Comparison of the evacuation time between the control volume model and SIMULEX.

Evacuation	Time (min)	
	Present ($R=1$)	SIMULEX
All persons have evacuated the 2 nd floor	363 sec (6.1 min)	247 sec (4.1 min)
All persons have evacuated the 3 rd floor	511 sec (8.5 min)	333 sec (5.6 min)
All persons have evacuated the 4 th floor	659 sec (11.0 min)	452 sec (7.5 min)
All persons have evacuated the 5 th floor	807 sec (13.5 min)	541 sec (9.0 min)
All persons have evacuated the 6 th floor	955 sec (15.9 min)	655 sec (10.9 min)
All persons have evacuated the 7 th floor	1103 sec (18.4 min)	777 sec (12.9 min)
All persons have evacuated the 8 th floor	1251 sec (20.9 min)	882 sec (14.7 min)
All persons have evacuated the 9 th floor	1177 sec (19.6 min)	877 sec (14.6 min)
All persons have evacuated the building	1436 sec (23.9 min)	1095 sec (18.3 min)

2.4.4 Effect of different specific flows

In order to study how coefficient of flow rate would affect the simulation results, we input the parameters of NFPA [1] (case 2) and the values of their investigation and empirical practice (case 7) as well. The results are compared and illustrated in Fig. 2-15. In case 2, the evacuees of the 2nd floor, 6th floor, 8th floor and 9th floor entered the stairwell at 363 sec, 955 sec, 1251 sec, and 1177 sec, respectively. While in case 7, the evacuees enter the stairwell at 477 sec, 1260 sec, 1652 sec and 1572 sec, respectively. The total evacuation time for the evacuees to ground floor is 23.94 minutes for case 2 and 31.60 minutes for case 7, which shows that the lower specific flow rates delay the evacuation time for 7.66 minutes.

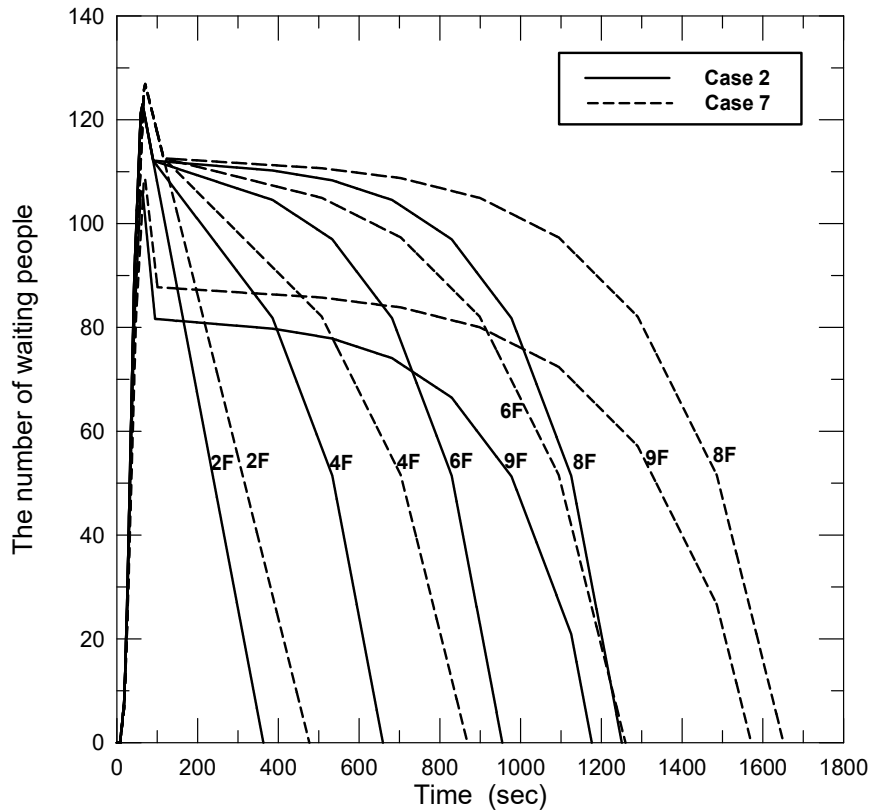


Fig. 2-15 The simulation results for different specific flow rates.

Table 2-5 presents the total evacuation times for case 1 to case 7. In case 2, merge flow ratio R is equal to 1 and the evacuees spent 23.9 minutes to complete evacuation, which is the quickest compared to case 1, 3, and 4 when R is equal to 0.1, 10, and 100 respectively. The bigger the R value is, the quicker the evacuees of high floors arrive at the ground floor. The 2nd floor evacuees are the first to reach the ground floor when R is very small. The higher value V_s explains why case 5 needs shorter period of time for total evacuation than case 6. In case 7, the values of exit specific flow and stair specific flow are the lowest compared to other cases, which results to the longest time for total evacuation. Comparing with the velocity of walking, coefficient of flow rate plays an important role in shortening the evacuation time and so to the safety of the evacuees.

Table 2-5 The results of evacuation time for different scenarios (minutes).

Case No.	1	2	3	4	5	6	7	NFPA [1]
Time	25.6	23.9	24.6	25.2	23.8	23.9	31.6	25.3

As mentioned previously, the control volume model was developed by a hydraulic

analogy based on homogeneous flow during evacuation process. In this chapter, the model uses two different methods to simulate people movement and predict evacuation time for high-rise buildings. The first is a hydraulic model, the NFPA method by Fahy [1], based on the three fundamental characteristics of crowd movement: density, speed, and flow. The second methodology is the control volume concept for people continuous flows through the exit. In addition, the factor of merge flow ratio is developed to be used in the analysis of emergency evacuation relative to the stair flow and exit flow. The numerical results of this model have shown to be in good agreement with NFPA calculation and SIMULEX [5] under the same assumptions. However, the different merge ratios cause completely different in terms of the number of people stagnation for each floor at same time.

In fact, modelling results are dependent both on the assumptions made and the limitations of the modelling tools used. Ronchi and Nilsson [6] showed that evacuation models not only need to consider the possible simulation of various occupant compositions but also the global impact they may have on the evacuation process e.g, their need for assistance, the formation of emerging groups with their assistants or others, etc.

This chapter provides just a beginning in analyzing the additional human behavior-related factors that may impact movement beyond classic hydraulic calculation method. To simulate realistic evacuation, data are needed on delay times, the effect of fatigue, and travel times for a range of occupants, etc. Galea et al. [7] also highlighted three fundamental components of high-rise building evacuations that are not currently fully represented in evacuation models, namely (1) the impact of fatigue, (2) the impact of group dynamics, and (3) the impact on evacuation dynamics of disabled people.

In this chapter, the calculation algorithm is based on the homogeneous flow. If the non-homogeneous flow or heterogeneous population is considered in this model, the calculation of simulation can merely decrease the walking speed and specific flows due to the lower speed or larger space requirements. For example, while the parameters of walking speed, exit specific flow, and stair flow in the case 1 are replaced by 0.5 (m), 0.65 (p/s.m), and 0.5 (p/s.m), respectively. The evacuation time for this case is estimated at 56.8 minutes. This result takes much longer time than that of case 1 for evacuation. As expected, decreasing the value of specific flow will increase the evacuation time.

Note that the blocking effect occurs even if the number of occupants with disabilities is minimal. Moreover, average movement speeds in the literature for very dense evacuations and 9/11 World Trade Center evacuation are significantly lower than that both current study and average values from literature [8]. In particular, when

the crowd is very dense, they yield unnatural emergent behavior such as individual stopping and waiting for space to clear up [9].

2.5 Conclusions of chapter

The main aim of this chapter is to analyze the resident evacuation of the high-rise building using the control volume model. The simulation process is divided into 5 stages. The simulation results provide the insights to the effects of different walking speed, coefficient of flow rate, and merge flow ratio on the dynamic change and number of the occupants stagnating for each floor in various time scales.

In this chapter, it is found that the merge flow ratio influences sequence of floors to be evacuated and time required for complete evacuation when coefficient of flow rate and velocity of walking remained a constant. It consumes least time for total evacuation when merge flow ratio R is equal to 1. The occupants of the lower floors finish evacuation sooner when R is less than 1. The occupants of the higher floors arrive at safe areas sooner when R is more than 1, which is similar to NFPA [1] method. The simulation results are also illustrated that with same walking speed value, the influence of coefficient of specific exit flow and specific stair flow is obvious. The higher the coefficient value, the shorter the total evacuation time is. When stagnation happened in the floors, increasing walking speed do not influence much in shortening the evacuation time.

By simplifying the factors of walking speed and flow coefficient, the evacuation of high-rise building is modeled using the control volume model. It should be noted that the merge flow ratio does not stay constant as many factors affect the descending evacuation process such as the physical capabilities and psychological conditions of the occupants, the development situation of the fire, and the surrounding of the architectures. It well known that occupant's life safety depends on whether occupants can evacuate safely before untenable conditions occur. Therefore, the evacuation of an engineered design requires a balanced comparison of predicted fire conditions and realistic evacuation predictions. The time required to egress called RSET consists of detection time, response time and movement time. To achieve safe evacuation and to enhance the Available Safe Egress Time (ASET), understanding human safety factors such as smoke, heat, visible distance and temperature are also important. In this chapter, the dynamic characteristics of the evacuation process at each time-step for each of the exits have been derived. Although this model is more complicated in calculation than NFPA, it is proven to identify the relationship among time, exit and the number of people stagnating and understand what happens during evacuation in high-rise buildings. The various merging behaviors at floor-stair of high-rise building

based on the different ratios of descending stair entry flow and exit flow have also been investigated which might be useful in building designing to assess buildings and provide new thoughts for future high-rise building evacuation simulations. In order to better align to the real-world evacuation process and understand the dynamics of the evacuees in time scale, it is expected that recent experimental studies on how walking speed and coefficient of flow rate changed can be built in this model in the foreseeable future.

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Chapter 3

*Study on mass evacuation during fire drills in a stairwell
of superhigh-rise buildings*

Chapter 3: Study on mass evacuation during fire drills in a stairwell of super high-rise buildings

3.1 Introduction of chapter

In this chapter, human movement characteristics in the stairwell of super high-rise buildings have been investigated. Based on fire drills, a total 229 participants and 7 cases of evacuation were performed in Taipei 101 and New Taipei City Hall which are about 508m and 140m tall, respectively. Within these cases, cases 1 to 6 were carried out in Taipei 101 and case 7 was carried out in New Taipei City Hall. The processes of evacuations were recorded by the cameras and observers in the stairwells and the data were extracted out manually. The speed characteristics of occupants when evacuating down in the stairwells for various floor intervals have been presented and analyzed. The mean speeds of cases 1 to 6 measured for vertical speeds concentrate within in a range from 0.22~0.24 m/s and the walking speeds are within 0.61~0.65 m/s. In cases 1 to 6, the temporal maximum density of occupant on the stair landing was 1.8 person/m². For case 7, the mean vertical speed and walking speed are 0.31 m/s and 0.98 m/s respectively, with the temporal maximum density of the occupant on the stair landing, 1.3 person/m². In addition, some evacuation behaviors were observed and discussed such as overtaking, group movement, and use of the cell phone, etc. In this chapter, the results are important for improving fundamental parameters to evacuation models in super high-rise buildings and compared with the results found from other studies for evacuees without impairment.

3.2 Experiments

3.2.1 Building layout

The evacuation experiments were conducted on Taipei 101 and New Taipei City Hall. Taipei 101 once the world's tallest building, rising 508 m, is located at the east district of downtown Taipei City and the elevation view of the building is shown in Fig. 3-1(a). There are mainly shopping malls from ground floor to the 4th floor, while there are all business offices and refuge spaces on the floors from the 6th floor to the 84th floor. In the between the 85th floor and the 88th floor, there are restaurants. The 89th floor is used to the observatory floor. The floors between the 90th and the 101st floor are used to the mechanical and communicational floors. Moreover, New Taipei City Hall is a 34-floor structure with a height of 140.5m as shown in Fig.3-2. On a typical day, the number of occupants is approximately 12,000 and 3,500 in Taipei 101 and New Taipei City Hall, respectively.

There are two safety routes of emergency evacuation in Taipei 101 on the regular floors. According to the emergency responses plan of Taipei 101, when evacuation takes place for emergency events such as fires, all the evacuees should choose one of these two evacuation staircases where evacuees can leave the building directly to ground floor, as shown in Fig. 3-1(b).

It should be noted that the evacuation stairwell of Taipei 101 is divided into two parts. The main part is between the 7th floor and the 89th floor in which each floor contains 2 flights of stairs and total 21 steps with the riser height of 20.0 cm and the tread of 24.0 cm as shown in Fig. 3-3(a). The evacuation stairwell of New Taipei City Hall is divided into three parts. The main part is between the 8th floor and 19th floor in which each floor contains 2 flights of stairs and total 25 steps with the riser height of 16.0 cm and the tread of 27.0 cm as shown in Fig. 3-3(b). The detail height and length of each floor interval on these two buildings are as shown in Table 3-1.

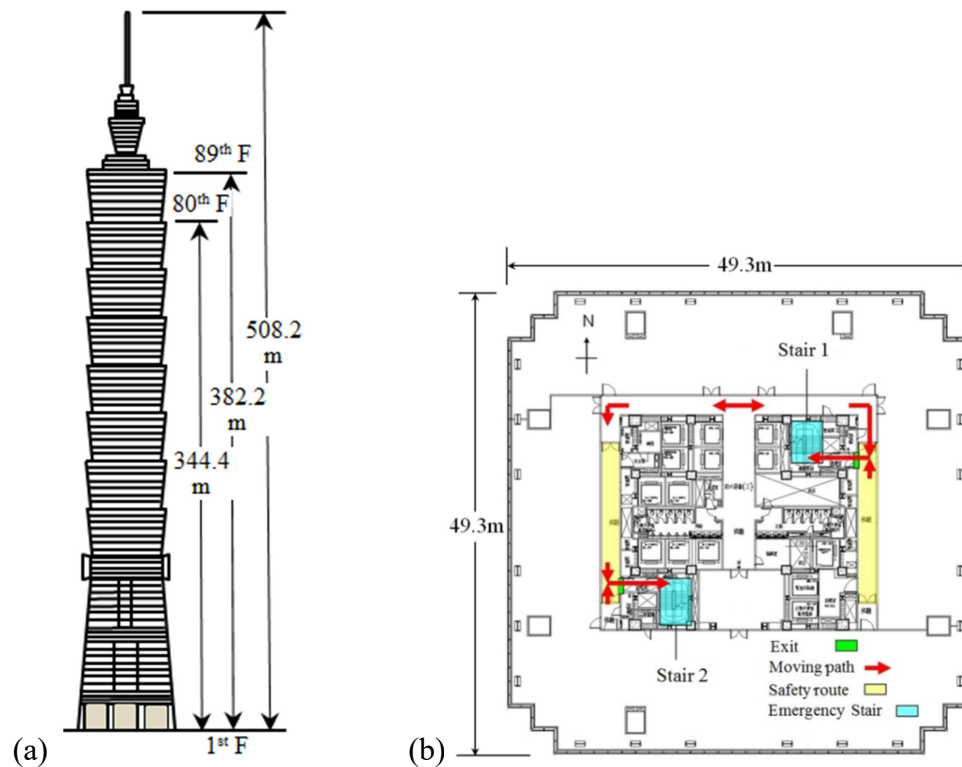


Fig. 3-1 The schematic view of Taipei 101 (a); typical floor layout of evacuation strategy (b).

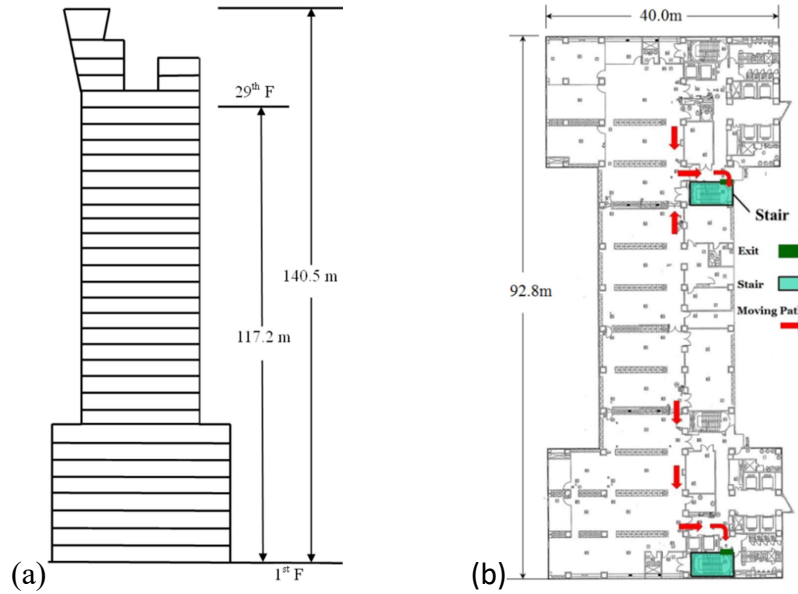


Fig. 3-2 The schematic view of New Taipei City Hall (a); typical floor layout of evacuation strategy (b).

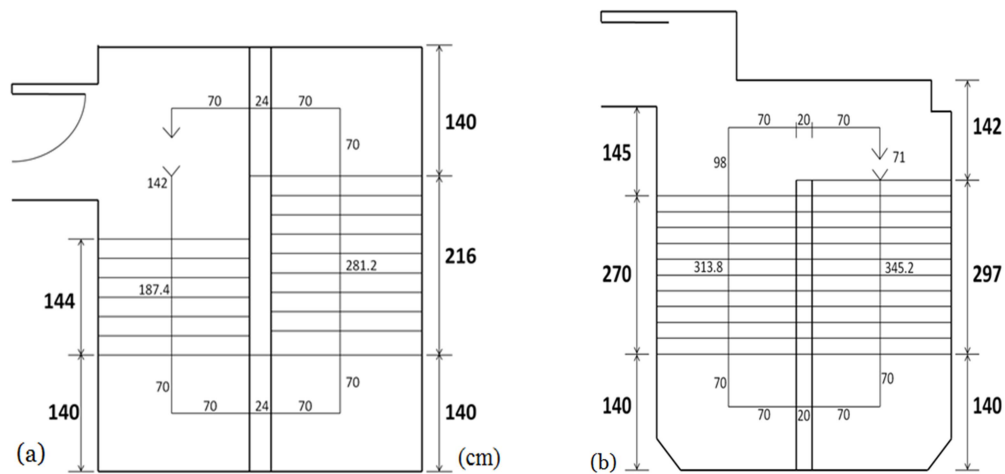


Fig. 3-3 Dimension of building stairs, Taipei 101 stair section on the 7th-89th floor (a); New Taipei City Hall on the 8th-19th floor (b).

Table 3-1 The size of stairs

Building	Floor	Height	Length	Riser	Tread	Width
Taipei 101	1 st -6 th	6.3m	17.229m	20.00cm	24.0 cm	1.4 m
	7 th -89 th	4.2m	11.486m			
New Taipei City Hall	1 st -7 th	4.45m	13.76m	16.00cm	27.0cm	1.4 m
	8 th -19 th	4.04m	12.88 m			
	20 th -29 th	4.17m	13.05m			

3.2.2 Definition of speed

For detailed analysis of the movement characteristics, the walking speed v_l and the vertical speed v_h are calculated using the following equations in this chapter, respectively:

$$v_l = \frac{L}{\Delta T}; \quad v_h = \frac{H}{\Delta T} \quad (3-1)$$

where L is the total length of the floors interval, H is the total height of the floors interval, and ΔT is the time interval of evacuation. For example, the evacuee moves down from the 3rd floor to the 1st floor as shown in Fig. 3-4 where the length and height of floor intervals can be calculated by $L = L_1 + L_2 + \dots + L_9$ and $H = H_1 + H_2$, respectively. The length of the adjacent floor is obtained from the inclination length and the distance of a participant through a stair landing between two adjacent floors. Because there is the mass evacuation in this experiment, the distance of a participant through a stair landing is simplified to walk along the middle line of the landing (see Fig. 3-3) as the same as calculated in NFPA [1] and Refs. [2-6].

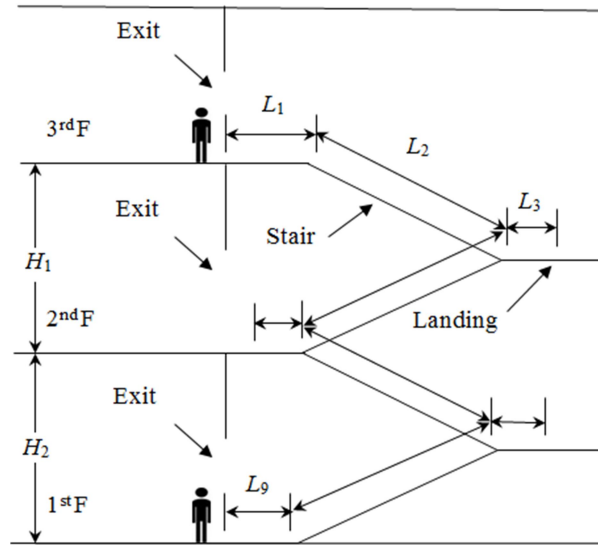


Fig. 3-4 Graphical description of walking speed calculation.

In addition, the length Δl (m) of the adjacent floor can be also obtained from the equation and shown as follows [6, 7].

$$\Delta l = n_s l_{inclination} + (n_f - 1) l_{turning} \quad (3-2)$$

where $l_{inclination}$: is the inclination length of a step,

n_s : the number of steps between two adjacent floors,

$l_{turning}$: the motion distance of a participant through a stair landing,

n_f : the number of flights two adjacent floors includes.

According to the size of riser and tread, $l_{inclination}$ is 31.24 cm for Taipei 101 on the

7th-89th floor and 31.38 cm for New Taipei City Hall on the 8th-19th floor (see Fig. 3-3 and Table 3-1). For Taipei 101, n_s and $l_{turning}$ are 15 and 682 cm, respectively. n_s and $l_{turning}$ are 21 and 629 cm for New Taipei City Hall, respectively. n_f is 2 for both buildings. Thus the length of each stair section Δl (m) can be calculated, and it is 11.49 m for Taipei 101 and 12.88 m for New Taipei Hall.

3.2.3 Outline of evacuation in the experiment

In this chapter, 7 cases were conducted to investigate the occupant characteristic of mass evacuation in different heights as shown in Table 3-2. Cases 1 to 6 were carried out in Taipei 101 in March, 2012 and case 7 was carried out in New Taipei City Hall in September, 2013. There were 229 participants in the experiments and 47.6 % were male. For cases 1 to 4, evacuees using stair 1 on the 89th to the 86th floor were numbered from 1 to 25, 26 to 51, 52 to 77, and 78 to 107, respectively. For cases 5 to 6, evacuees using stair 2 on the 54th and the 40th floor were numbered from 108 to 138, 139 to 168, respectively. Another 61 participants took part in the case 7 on the 29th floor.

Table 3-2 The description of cases 1 to 7.

Building	Case	Start floor	Participates			ID
			Male	Female	Total	
Taipei 101	Case 1	89 th F	13	12	25	1~25
	Case 2	88 th F	11	15	26	26~51
	Case 3	87 th F	11	15	26	52~77
	Case 4	86 th F	16	14	30	78~107
	Case 5	54 th F	17	14	31	108~138
	Case 6	40 th F	13	17	30	139~168
New Taipei City Hall	Case 7	29 th F	28	33	61	169~229

It was around 1,500 people and 500 people to participate into the fire drills in Taipei 101 and New Taipei City Hall, respectively. All the evacuees who participated in the experiments were randomly selected for each floor and agreed to take part in the experiments and also were the employees in the Taipei 101 and New Taipei City Hall. At the beginning of the experiments, all evacuees were initially stayed on the floor. After the fire drill broadcast, all of the participants entered the stair under the guidance of the self-defense fire fighter at the same time. It should be noted that the strategy of phased evacuation was used to avoid the merge flow at exits and the occupant flow blocked during the fire drills at the initial time.

Moreover, all of the participants were not impaired and informed to perform a fire drill. The influencing factors on movement of occupant such as pre-movement behavior, age, merge flow, psychology, contour flow, and body size were not considered in this chapter.

3.2.4 Data collecting method

For cases 1 to 6 in Taipei 101, the whole process of evacuation was recorded by the 7 CCTV cameras and 12 observers in the stairwells, as the schematic view was shown in Fig. 3-5. For case 7, the evacuation process was recorded by the 4 CCTV cameras and 4 observers, which were located on the stair landing of the 29th, 20th, 8th, and 1st floors, respectively.

The heights and lengths of different floor intervals for Taipei 101 and New Taipei City Hall were summarized as shown in Table 3-3. To assist data collecting and case identification, each participant was asked to stick numbered and colorful stickers on the arm or on the front of chest with respected to each case during the evacuation process as shown in Fig. 3-6(a). In this chapter, all the participants in the video recordings were manually tracked to get the time when the evacuees moved in the stairwells. In addition, the observers (seen in Fig. 3-6(b)) not only can support to identify the participants and feedback the human behaviors observation but also to prevent accidents during the experiments.

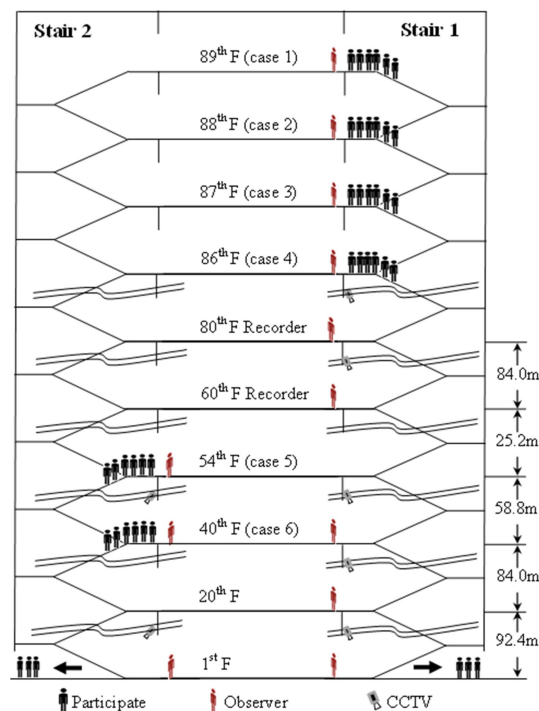


Fig. 3-5 The schematic view of Taipei 101 stairwell.

Table 3-3 Heights and lengths of different floor intervals.

Building	Floor	Route (m)	
		Height	Length
Taipei 101	80 th F - 60 th F	84.0	229.72
	60 th F - 40 th F	84.0	229.72
	40 th F - 20 th F	84.0	229.72
	20 th F - 1 st F	92.4	252.69
	Total	344.4	941.85
	54 th F - 40 th F	58.8	160.80
	40 th F - 1 st F	176.4	482.42
New Taipei City Hall	Total	235.2	643.22
	29 th F - 20 th F	37.53	117.45
	20 th F - 8 th F	48.48	154.56
	8 th F - 1 st F	31.15	96.32
New Taipei City Hall	Total	117.16	368.33

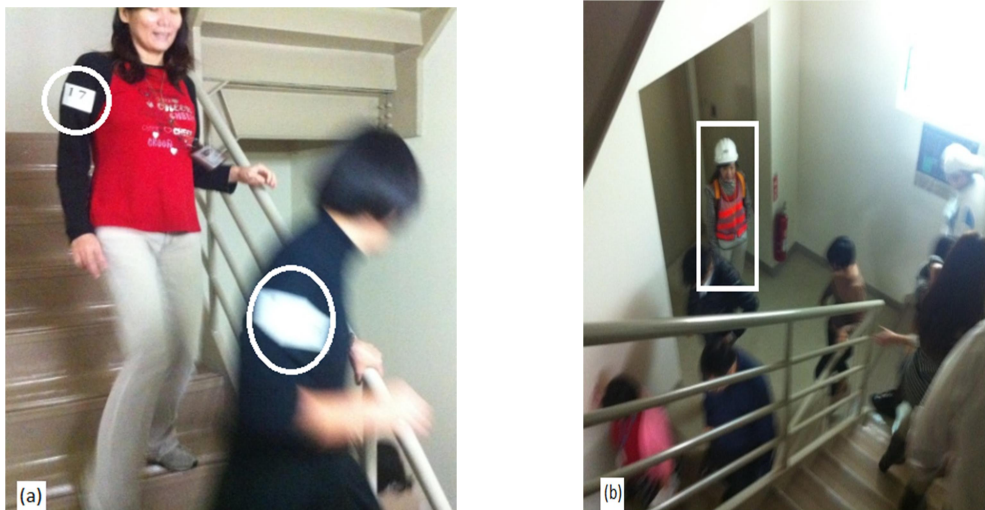


Fig. 3-6 Snapshots of evacuation process. The circles show the stickers (a); the rectangular shows the observer (b).

3.3 Results and discussions

3.3.1 The cases 1 to 4

In total 107 participants took part in the cases 1 to 4 (as shown in Table 3-2) to explore the mass evacuation characteristics in Taipei 101. The participants moved down from the 89th floor to the 86th floor are 25, 26, 26, and 30, respectively. One goal of this study is to investigate into the walking speed of mass evacuation in a super high-rise building. To avoid the evacuation flow affected by the merge effect

during the experiment, the recording data was only analyzed from the 80th floor to the 1st floor. In addition, it can be found that the participant needs to move down from the height of about 344m (as shown in Table 3-3) to the ground floor i.e. the length of about 942m in total. For the cases 1 to 4, the mean vertical speed v_h and the mean walking speed v_l of each participant for cases 1 to 4 are presented in Figs. 3-7 and 8. It took about 1,500s in average to move down from the 80th floor to the 1st floor. In Fig. 3-7, it can be found that most of the v_h values concentrate within a range from 0.19 m/s to 0.26 m/s, and the v_l values are within a range from 0.50 m/s to 0.70 m/s as shown in Fig. 3-8.

Furthermore, to provide the variations of walking speed during the evacuation for a super high-rise building, we investigated into the time intervals in each 20 floors from the time when the participants entered the 80th floor. The speed of each participant walking through each 20 floors interval can be obtained by using the Eq. (3-1). The results of the mean and median speeds of v_h and v_l in each 20 floors interval for cases 1 to 4 are presented in Table 3-4. As shown in Table 3-4, the average vertical speed v_h and walking speed v_l are 0.228 m/s and 0.624 m/s, respectively. In addition, the median speeds in v_h and v_l are nearly the same as the mean speeds. The results also indicate that the speeds show variations in each 20 floors interval, though the mean speeds are slightly changed for these cases. The average vertical speed obtained from this experiment is relatively lower than those reported by Ma et al. [8]. According to their report, the mean vertical speed when evacuating down from the 101st floor to the ground floor was about 0.28 m/s.

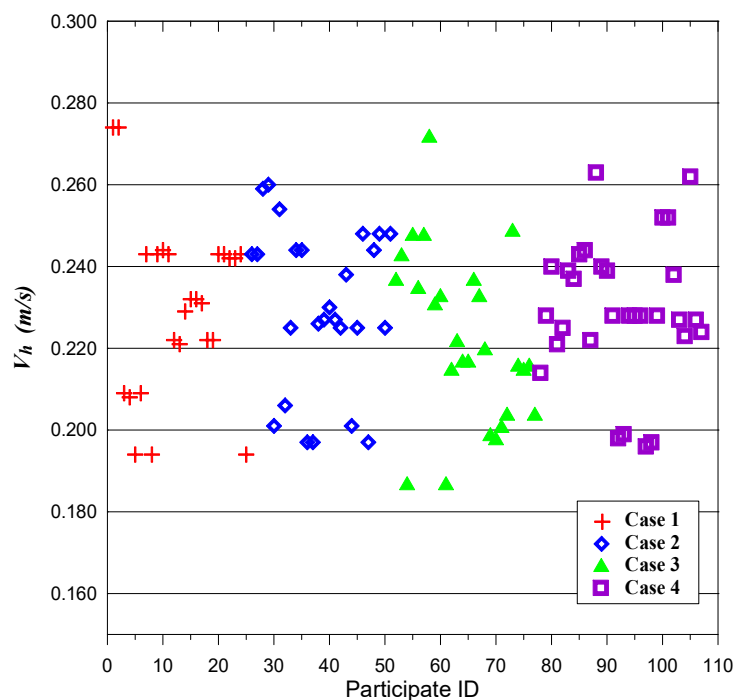


Fig. 3-7 The mean vertical speed v_h of each participant for cases 1 to 4.

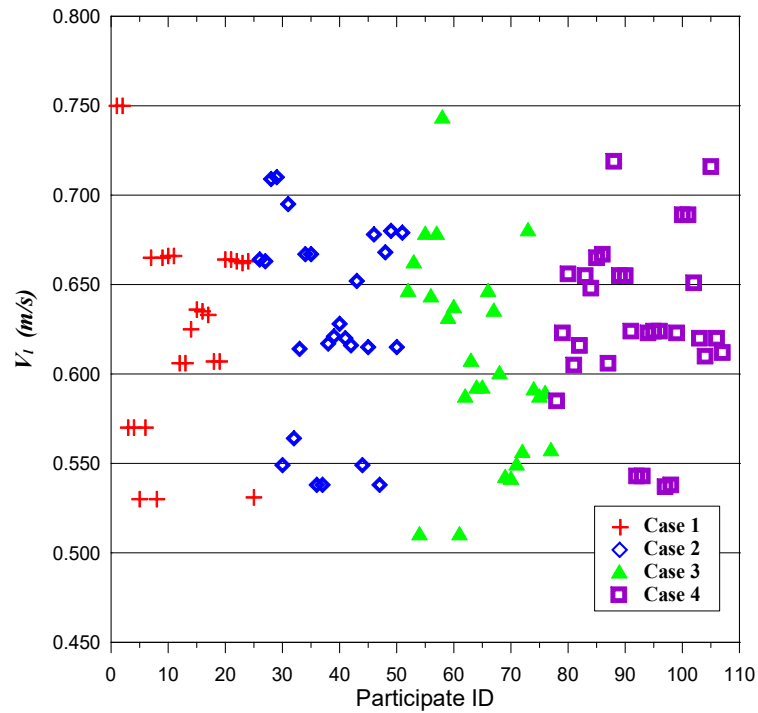


Fig. 3-8 The mean walking speed v_l of each participant for cases 1 to 4.

Table 3-4 The results of movement speeds for cases 1 to 4.

Case	Velocity (m/s)		Floor interval				
			80 th F	60 th F	40 th F	20 th F	80 th F
			- 60 th F	- 40 th F	- 20 th F	- 1 st F	- 1 st F
Case1	mean	v_h	0.265	0.236	0.220	0.217	0.230
		v_l	0.724	0.646	0.601	0.594	0.629
	median	v_h	0.268	0.217	0.212	0.215	0.232
		v_l	0.734	0.594	0.579	0.588	0.635
Case2	mean	v_h	0.276	0.246	0.206	0.215	0.230
		v_l	0.754	0.673	0.563	0.589	0.629
	median	v_h	0.273	0.245	0.196	0.226	0.229
		v_l	0.748	0.669	0.536	0.617	0.625
Case3	mean	v_h	0.260	0.222	0.234	0.202	0.222
		v_l	0.710	0.606	0.639	0.552	0.608
	median	v_h	0.243	0.216	0.218	0.204	0.219
		v_l	0.664	0.591	0.596	0.557	0.597
Case4	mean	v_h	0.279	0.239	0.204	0.226	0.230
		v_l	0.764	0.653	0.557	0.618	0.628

Average	median	v_h	0.278	0.225	0.208	0.214	0.228
		v_l	0.760	0.616	0.569	0.585	0.624
	mean	v_h	0.270	0.236	0.216	0.215	0.228
		v_l	0.738	0.645	0.590	0.588	0.624
	median	v_h	0.266	0.226	0.209	0.215	0.227
		v_l	0.727	0.618	0.570	0.587	0.620

It is well known that when the density of occupants in the stairwell is low, evacuees can move freely, thus the one can move as fast as possible. However, with the increase the density of occupants in the stairwell, evacuees have to slow down and queue to avoid colliding into the front occupants. In reality, the density of occupant flow during the evacuation drill is dynamics in the stairs. As mentioned in the previous section 2.4, the process of evacuation for cases 1 to 6 was recorded by the 7 CCTV cameras and 12 observers in the stairwells, we cannot present the density of the whole process except the CCTV cameras record. According to the video data, the temporal maximum density of occupant on the stair landing was 1.8 person/m^2 for cases 1 to 4. It should be noted that the temporal maximum density in cases 1 to 4 was calculated including the occupants who took a short break on the landing. Moreover, feedbacks from the participants of this experiment indicated that congestion of the flow was observed in few locations during the evacuation process because of the merge flow and the fatigue participants.

The maximum and minimum vertical speeds of each participant for cases 1 to 4 in each 20 floors interval are investigated as shown in Fig. 3-9. The maximum and minimum vertical speeds of each participant in the experiment are 0.414 m/s and 0.133 m/s, respectively. From Fig. 9, the mean/median speed firstly decreases sharply and then decreases slightly. At the last two intervals of evacuation, the speeds of participants arrive at the steady values. The tendency of mean vertical speed of each participant in different floor intervals is also different from the reports by Ma et al. [8]. They had investigated that the mean speed first decreased and then increased slightly and arrived at the biggest value in the penultimate stage. At the last stage of the evacuation, the speeds of the participants decrease sharply [8].

Feedbacks from the observers of this experiment indicated that the overtaking phenomenon is observed commonly for young participants, and a few participants had inadequate physical strength and then took a short break during the evacuation. For cases 1 to 4, participants realized it might be fatigue if they began to hurry up, thus they began to keep moving steady to preserve their physical strength. However, at the last two stages of evacuation, the speeds decrease obviously. Because of the fatigue

reason, the decreasing speed at the last two “20 floors interval” led to increase of density in the stair, and then decreased the movement efficiency.

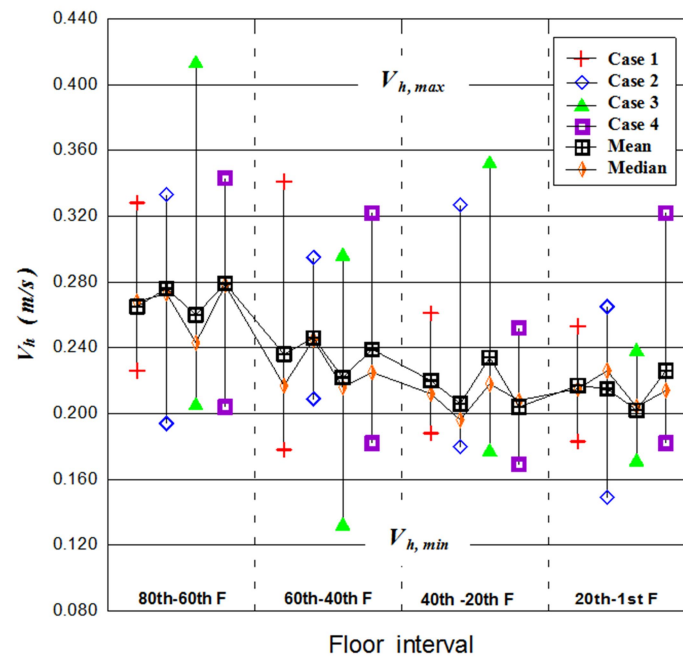


Fig. 3-9 The vertical mean speed v_h of each participant in each 20 floors interval.

3.3.2 The cases 5 to 7

For cases 5 to 6, participants using stair 2 on the 54th floor and the 40th floor of Taipei 101 were numbered from 108 to 138, 139 to 168, respectively. For case 7, 61 participants took part on the 29th floor of New Taipei City Hall. In addition, we investigated the moving speed at 40th floor and ground floor for case 5. For case 6, we investigated the moving speed at the 1st floor only.

The vertical speed v_h of each participant for cases 5 and 6 is shown in Fig. 3-10. It is clearly shown that there is a huge difference for the participants in case 5. The maximum and minimum vertical speeds of each participant are 0.392 m/s and 0.156 m/s, respectively. Due to the reasons as mentioned in the previous cases, few participants were running to overtake others thus they can finish the evacuation as soon as possible, and few participants needed to take a short break during the evacuation process. The observers also indicated that there were some participants walking together to help each other and some participants using the cell phone resulted that people moved slow and were not so easy to overtake during the evacuation process. According the video data, the temporal maximum density of occupants on the stair landing was 1.6 person/m² for cases 5 to 6. As mentioned previously in cases 1 to 4, the result of temporal maximum density in cases 5 to 6 was

calculated including the occupants who took a short break on the landing.

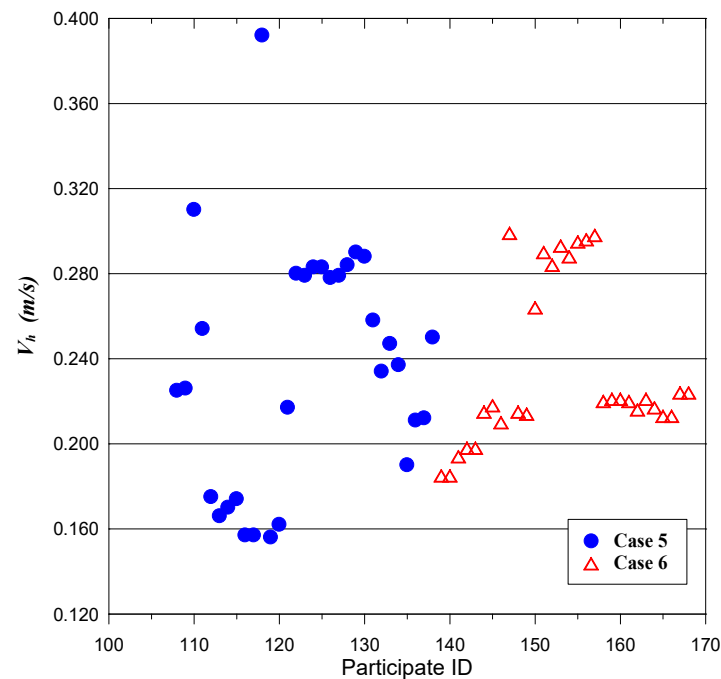


Fig. 3-10 The mean vertical speed v_h of each participant for cases 5 and 6.

Fig. 3-11 shows the results of vertical speed v_h of each participant for cases 7. It shows that the vertical speeds concentrate within a range from 0.30 m/s to 0.32 m/s and a smaller difference than that in the cases 1 to 6. In this case, all of the participants not only were not impaired but also were asked to follow the self-defense fire fighters to evacuate at fire drill. In Taiwan, the self-defense fire fighters of high rise office buildings are organized by the employees to extinguish fire and evacuate the occupants at the initial stage when fire occurred. For case 7, the temporal maximum density of occupants on the stair landing was 1.3 person/m². During the evacuation process, the behaviors of taking a short break or using the cell phone were not found in the case. However, only a few participants had the overtaking behavior. Therefore, the whole process in case 7 can be regarded as the group evacuation behavior instead of individual free movement.

The results of movement speeds for cases 5 and 6 are shown in Table 3-5. For case 5, the speed of the 54th floor to the 40th floor is faster than that of the 40th floor to the 1st floor. It is well known that the participants move fast at the initial phase of evacuation process and then feel tired later which make them slow down. From Table 3-5, we can also find that the mean speed of case 5 is nearly the same as that of case 6.

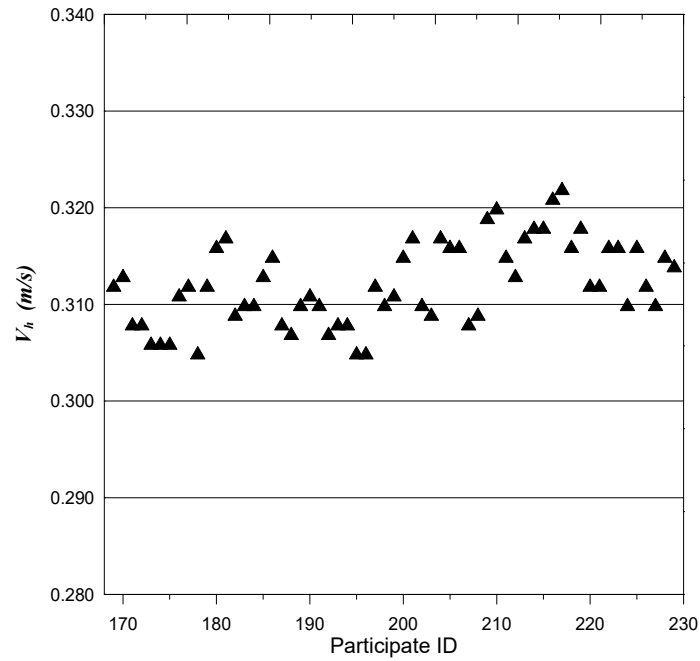


Fig. 3-11 The mean vertical speed v_h of each participant for case 7.

Table 3-5 The results of movement speeds for cases 5 and 6.

Case	Velocity (m/s)		Floor interval		
			54 th F-40 th F	40 th F-1 st F	54 th F-1 st F
Case 5	mean	v_h	0.263	0.229	0.236
		v_l	0.720	0.626	0.646
	median	v_h	0.294	0.224	0.237
		v_l	0.804	0.611	0.648
Case 6			40 th F-1 st F		
	mean	v_h	0.235		
		v_l	0.642		
	median	v_h	0.220		
		v_l	0.602		

Table 3-6 shows the results of movement speeds for case 7. It shows an interesting phenomenon of the movement speed distribution for this case. The mean vertical speed first increases slightly and arrives at the highest value at the last phase of the evacuation. Except for the group evacuation, the other possible reasons for the speed distribution might be due to the psychology change and overtaking. Self-defense fire fighters and participants then recognized that it might take too much time for the

evacuation if they keep moving slow, thus they began to hurry up. In addition, overtaking was not so easy because participants were asked to follow self-defense fire fighters to evacuate when the fire drill began. Overtaking only occurred at lower floors in this case. In case 7, there were 3 self-defense fire fighters who were consisted of New Taipei City staff and assigned to guide the participants to evacuate after the fire alarm broadcast. One of the self-defense fire fighters was the leader to lead the participants and two other self-defense fire fighters needed to assist/help the participants for disabilities, older people during the evacuation process. In fact, the participants were with the healthy and young in this case who can follow others without congestion and delay.

Table 3-6 The results of movement speeds for case 7.

Case	Velocity (m/s)		Floor interval			
			29 th F-20 th F	20 th F-9 th F	9 th F-1 st F	29 th F-1 st F
Case 7	mean	v_h	0.291	0.322	0.327	0.312
		v_l	0.909	1.025	1.011	0.981
	median	v_h	0.293	0.323	0.328	0.312
		v_l	0.918	1.030	1.014	0.980

It should be also noted that the mean vertical speed v_h of the 20th - 8th floor interval is lower than that of the 8th -1st floor interval. However, the mean walking speed v_l of the 20th -8th floor interval is higher than that of the 8th -1st floor interval. The reason for the inconsistent results of the vertical and walking speed in case 7 is that the sizes of stair are different in these two sections as shown in Tables 1 and 3.

Figs. 3-12 and 3-13 show the maximum and minimum vertical and walking speeds of each participant for cases 1 to 7. It can be clearly seen that the mean speeds in cases 1 to 6 are significantly lower than that of the results in case 7. The mean vertical speeds of cases 1 to 6 concentrate within in a range from 0.22~0.24 m/s i.e. the walking speeds are within 0.61~0.65 m/s. Compared to mean/median value, the biggest and smallest deviations in this chapter are the cases 5 and 7, respectively.

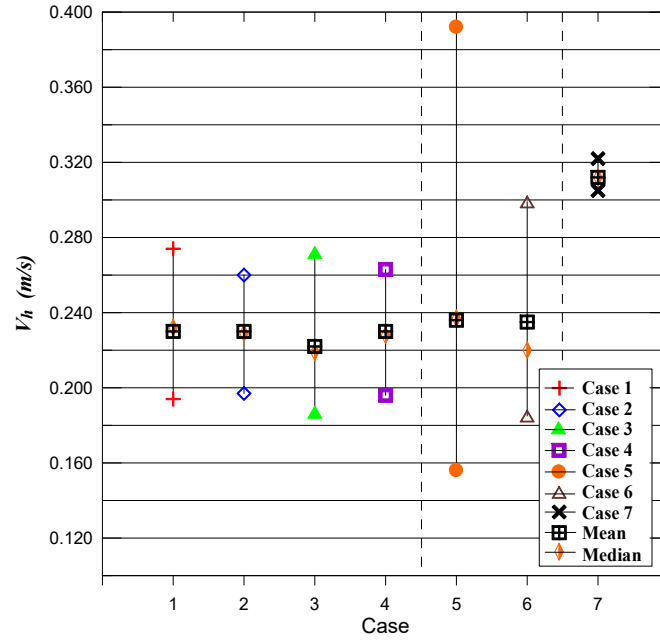


Fig. 3-12 The vertical speeds v_h for cases 1 to 7.

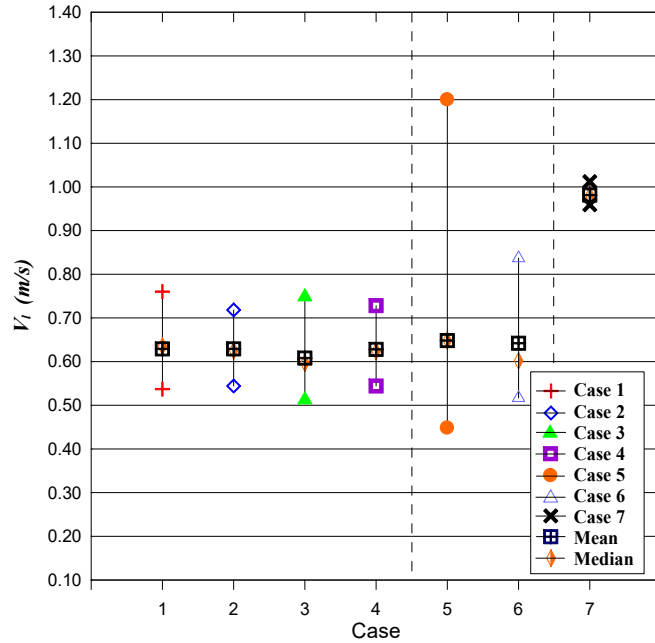


Fig. 3-13 The walking speeds v_l for cases 1 to 7.

3.3.3 Comparison to similar studies

Beyond the differences in the various types of buildings, occupancies, and evacuation conditions being studied, measurement methods significantly varied. Thus, comparison of the data with the similar conditions is naturally limited in scope. Table 3-7 summarizes movement speeds reported in the literature. It can be found that the fundamental movement speed is walking speed v_l which provides basic input for the

engineering application of building facilities design. The mean walking speed in the cases 1 to 4 calculated from the 80th -1st floor is 0.624 m/s which is similar to the movement speeds of occupants without disability in the Ma et al. [8] and Kadokura studies [9] (0.62 m/s). Ma et al. studied the evacuation of a single pedestrian from the 101st floor to the first floor in Shanghai World Financial Center, which is about 470m tall. When we compare the mean vertical speed, we can see that the value of v_h in this chapter is relatively lower than that reported by Ma et al (0.28 m/s). However, it took about 2,000s for the evacuees to move down from the height of about 460m to the ground level [8]. If the vertical speed v_h is calculated as the Eq.(1), then the vertical speed of Ma et al. study can be modified as 0.23 m/s thus the result is similar as this study (0.228 m/s) for cases 1 to 4.

In addition, NIST [10] shows that the mean movement speed for buildings studied was 0.44 ± 0.19 m/s that represented more than 22,000 individual measurements in 30 stairs in 14 different buildings. It should be noted that the mean speed for occupants needing assistance, the ranges are revised to 0.11 to 0.33 m/s [10]. For case 7, the results contrast to the somewhat lower walking speeds found in the earlier studies. It can be considered as a special experiment because the results were carried out at the fire drill with the healthy and young participants.

Table 3-7 Summary of movement speed literature.

Study	Speed v (m/s)				Descriptions
	v_h		v_l		
	Mean	Median	Mean	Median	
Present					
Case 1-4	0.228	0.227	0.624	0.620	Within the 80 th -1 st floor
Case 5-6	0.236	0.229	0.644	0.625	
Case 7	0.312	0.312	0.981	0.980	Within the 29 th -1 st floor.
NFPA (Fahy, 2008)[1]					
Evacuation speed	-	-	0.85	-	D=0.54 person/m ² . Riser = 19.0cm, tread =25.4cm.
High-rise office building drill	-	-	0.61	-	D=1.3 person/m ² . Stair with full lighting.
	-	-	0.70	-	D=1.25 person/m ² . Stair with induced lighting.
	-	-	0.72	-	D=1.00 person/m ² . Stair with photoluminescent material (PLM) installation

	-	-	0.57	-	and induced lighting. D=2.05 person/m ² . Stair with PLM only.
Fang et al. [6]	-	-	0.807	0.786	0.362 m/s < v_i < 1.376 m/s
Peacock et al. [5]	-	-	0.48±0.16	-	Individual local movement speeds ranged from 0.056 m/s to 1.7 m/s
NIST [10]			0.44±0.19		Individual local movement speeds ranged from 0.07 m/s to 1.7 m/s.
Ma et al. [8]	0.28	-	0.62	-	Performed in Shanghai World Financial Central, which is about 470 m tall.
Building Center of Japan [3]	-	-	0.783	-	
Taiwan [4]	-	-	0.6	-	The value is used to performance design of the high-rise office buildings.
Koo et al. [11]	-	-	0.7	-	Non-disabled.
Boyce et al. [12]			0.70±0.26		With canes =0.32±0.12 m/s.
Kadokura [9]			0.62		During the drill

As mentioned previously, all of the evacuees were initially informed to participate in fire drills. As they were in good health, it could be expected that they didn't need assistance during the evacuation process. Therefore, it is difficult to know the movement by people with disabilities or the merge behaviors in this chapter. During the evacuation process, some of the participants carried important items with them, including handbag, briefcase, notebook, et al. and used mobile phones to communicate and inform the family or friends of the current situation. These behaviors will decrease movement speed and increase the pre-movement time for the evacuation process. Furthermore, people might have inadequate physical strength and need to take a short break during the evacuation, and will then lead to increase the density of evacuation and become the bottle-necking of movement. For case 7, the participants followed the self-defense fire fighter to evacuate resulting in a smaller deviation, which can be considered as a Leader-follower behavior. Some participants would follow others, even to a non-necking landing or stair.

3.4 Conclusions of chapter

In this chapter, mass stair movement characteristics such as mean vertical and walking speeds during super high-rise building evacuations were analyzed. A total 229 participants joined the fire drills by performing 7 cases in the experiments, which ranged from 29 to 80 floors i.e. 117m to 344m in height and 368m to 942m in length. Within the cases, cases 1 to 6 were carried out in Taipei 101 and case 7 was carried out in New Taipei City Hall. The results of this chapter are summarized as follows.

- 1) In the cases 1 to 4, the movement characteristics of mass participants egress from the 80th floor to the 1st floor were investigated. The temporal maximum density of occupants was 1.8 person/m² on the stair landing and congestion of the flow was observed in few locations. It took about 1,500s for each participant to move down from the 80th floor to the 1st floor. The results indicated that most of the v_h values are within a range from 0.19 m/s to 0.26 m/s, and the v_l values are within a range from 0.50 m/s to 0.70 m/s. For cases 1 to 4, the mean speeds v_h and v_l performed in this chapter are 0.23 m/s and 0.62 m/s, respectively.
- 2) In the cases 5 to 6, the movement characteristics of mass evacuation were conducted by egress drill from the 54th floor to the 1st floor and the 40th to the 1st floor, respectively. The temporal maximum density of occupants was 1.6 person/m² on the stair landing. The mean speeds in case 5 are nearly the same as those in case 6. Results of these two cases are about 0.24 m/s in vertical speed and 0.64 m/s in walking speed.
- 3) The mean speeds of cases 1 to 6 for vertical speed concentrate within in a range from 0.22~0.24 m/s and the walking speeds are within 0.61~0.65 m/s. This data is also in good agreement with the studies by Ma et al. [8] and Kadokura [9]. Therefore it is suitable to use this data for evacuation models or fire risk assessment for occupants without impairment. If the older, disabled, and impaired occupants are considered, the values of movement speed in evacuation models/fire risk assessments should be lower than the results of this chapter.
- 4) For case 7, the mean speeds in v_h and v_l are 0.31 m/s and 0.98 m/s, respectively. The values of this case were higher than those of cases 1 to 6 because this case was considered as a special situation where the evacuees were under a Leader-follower behavior during evacuation process. Therefore, the better executive behaviors of self-defense firefighters in fires will lead to the better performances of evacuation. It should be noted that the participants were with the healthy and young who can follow others without congestion and delay in this case.
- 5) During the evacuation process for all of the cases, some behaviors were observed

such as overtaking, a short break, group movement, and use of the cell phone. These behaviors will lead to increase the density of evacuation and interfere with the evacuation movement.

In this chapter, these results are important for improving fundamental parameters to evacuation models in a super high-rise building and consistent with previous studies for evacuees without impairment. However, as the results were obtained under fire drills and good health participants rather than real emergency situations, this results cannot represent the general features for disabled people, older people, and children. The merging behavior and relationship between walking speed and density are also not considered and investigated in this chapter. To totally understand overall exit times for super high-rise building evacuation, the better understandings of movement and behavior of occupants for the further researches are important and needed, particularly with various stair widths and the ratios of tread and riser, the factors of fatigue, the merging behaviors at the stair for mass evacuation, and the impact for disabilities on occupant movement speed and flow etc. in a stairwell.

Acknowledgements

I appreciate the valuable comments and constructive suggestions given by Prof. Ai Sekizawa.

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Chapter 4

*The Numerical Analysis of mass evacuation in Taipei 101
with control volume model*

Chapter 4: The Numerical Analysis of Mass Evacuation in Taipei 101 with Control Volume Model

4.1 Introduction of Chapter

Issues of safety evacuation of super high-rise buildings for emergencies have been attracting a lot of studies, especially after the disaster of WTC 9/11. In this chapter, the numerical results and dynamic processes of mass evacuation of a super high rise building are investigated by using the control volume model. The evacuation process of this model is divided into five stages and based on the assumptions of homogeneous flow with merge flow ratio where the exit flows from different floors meet and merge together. The super high-rise building, Taipei 101 is chosen for the object of evacuation simulation building, which is about 508m tall. Seven scenarios, which content as total building evacuation and phased evacuation, are analyzed by using various values of the parameters which influenced the evacuation process in the building including walking speed, coefficient of flow rate, and merge flow ratio etc. The numerical results of mass evacuation are found to be in good agreement with the result of the National Fire Protection Association (NFPA) [1] first-order approximation and indicate that the evacuation processes are highly dependent on the parameters of walking speed and specific flow. Furthermore, the dynamic characteristics of the evacuation process at each time-step for each floor are presented and discussed.

4.2 The descriptions of Taipei 101 and control volume model

4.2.1 Building layout

The super high-rise building, Taipei 101 is chosen for the object of evacuation simulation building in this study. Taipei 101 which was the world's tallest building, rising 508 m, is located at the east district of downtown Taipei City and the elevation view of the building is as shown in Fig. 3-1(a). There are 101 floors above the ground floor, as well as 5 basement levels. The tower is divided into 3 portions: lower section (7th -34th F), middle section (35th -58th F), and high rise section (59th -91st F).

There are mainly shopping malls from ground floor to the 4th floor, while there are all business offices and refuge spaces on the floors from the 6th floor to the 84th floor. Between the 85th floor and the 88th floor, there are restaurants. From the 89th floor to the 91st floor are used for sightseeing. The floors between the 92th floor and the 101st floor are used for the mechanical and communicational floors. On the top of each eight-floor section is a mechanic floor which includes mechanic, electric and

plumbing (MEP) system, ventilation system, garbage system, fire fighting water storage tank, fire protection shelter rooms, and outdoor shelter balcony. The 35th and 59th floors, the temporary shelter floors of the tower, are designated as the elevator bletransfer floor and sky lobby [2].

There are two pressurized stairwells provide the major escape routes for the occupants. When evacuation takes place for emergency events such as fires, all the evacuees should choose one of these two evacuation stairwells where evacuees can leave the building directly to ground floor, as shown in Fig. 3-1(b).

4.2.2 Space configuration

There is one 1.4 m clear width door at each stairwell entrance. The evacuation stairwell of Taipei 101 is divided into two parts. The main part is between the 7th floor and the 91st floor in which each floor contains 2 flights of stairs with 1.4m width and total 21 steps with the riser height of 20.0 cm and the tread of 24.0 cm as shown in Table 3-1. The length of the adjacent floor is obtained from the inclination length and the distance of a participant through a stair landing between two adjacent floors. Because there is mass evacuation in this chapter, the distance of a participant through a stair landing is simplified to walk along the middle line of the landing (see Fig. 3-3(a)) as calculated in Refs. [1, 3-7].

The length Δl (m) of the adjacent floor can be obtained from the equation and shown in Eq. 2-1 [6, 7].

Based on the prescriptive occupant load factors in Taiwan [5], the total number of occupants inside the building is estimated. Since the building consists of different functions, the whole building, Taipei 101 would be the peak usage during the office days. For example, the number of office occupants is based on the density of 0.125 person/m² of office space, and resulted in 170 persons on a typical floor of Taipei 101. According to the approved fire safety evacuation plan of Taipei 101, the number of occupants is approximately 12,200 on a typical day. The detail number of occupant, height and length of the routes and functions of different floors interval in Taipei 101 are as shown in Table 4-1.

4.2.3 Control volume model

4.2.3.1 Basic assumptions

The control volume model assumes that each individual passenger is an independent individual. During evacuation process, when the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface (control surface) is formed by connecting the occupants at the exit and that is changed with time as shown in Fig.2-1. The closed surface is changed with time and the summation of

different rate between the inflow and outflow. By setting the height of each individual as 1, the area of the closed surface is equal to the control volume, thus, the closed surface is called the control surface.

Table 4-1 The size of stairs and function of different floor intervals.

Floor interval	Route (m)		Occupants	Function
	Height	Length		
91 st - 89 th F	4.2	11.49	120	Sighting
90 th F	4.2	11.49	0	Sighting(The damper floor)
89 th F	4.2	11.49	200	Sighting
88 th - 85 th F	16.8	45.94	470	Restaurant (87 th F, mechanical floor)
84 th - 83 rd F	8.4	22.97	340	Office
82 nd - 75 th F	33.6	91.89	1190	Office (82 nd F, mechanical floor)
74 th - 67 th F	33.6	91.89	1190	Office (74 nd F, mechanical floor)
66 th - 59 th F	33.6	91.89	1190	Office (66 th F, mechanical floor; 59 th F, sky/lobby floor)
58 th - 51 st F	33.6	91.89	1190	Office (58 th F, mechanical floor)
50 th - 43 rd F	33.6	91.89	1190	Office (50 th F, mechanical floor)
42 nd - 35 th F	33.6	91.89	1190	Office (42 th F, mechanical floor; 35 th F, sky/lobby floor)
34 th - 27 th F	33.6	91.89	1190	Office (34 th F, mechanical floor)
26 th - 19 th F	33.6	91.89	1190	Office (26 th F, mechanical floor)
18 th - 9 th F	42.0	114.86	1360	Office (18 th -17 th F, mechanical floor)
8 th - 7 th F	8.4	22.97	0	Mechanical floor
6 th - Ground F	37.8	103.37	222	Shopping, office, and conference rooms

In addition, the evacuee flow is assumed as homogeneous, which means the evacuee walks with the same velocity, the evacuee flow from the door or exit is continuous, thus the specific flow is a constant. On each floor, the merge flow ratio of the descending stair entry flow and exit flow is also a constant. In addition, the pre-movement time-lag, alarming response, and broadcasting response are not considered. By setting the height of the occupant (each individual) as 1, the area of the closed surface is equal to the control volume. Assuming the occupant number per unit area as a constant, the transient area of the control volume can be easily derived from particle number within the control volume.

The total number of occupants flowing to the control volume at certain time point t has been presented as in Eq. 2-1 [8, 9]:

4.2.3.2 Occupant movement

In this study, the occupants' movements of emergency evacuation in the stairwell are mainly divided into five stages where stage 1 is the occupants departing from the room and arriving at the floor exit; stage 2 is the occupants descending to the next floor; stage 3 is the occupants of the $n+1^{\text{th}}$ floor merging with the crowd originally occupying the n^{th} floor; stage 4 is the combined crowd reaching the maximum capacity of the stairwell; stage 5 is the completion of the evacuation [8]. In the following context, detailed calculations based on these occupant movement characteristics will be provided.

4.3 Modeling and analysis

4.3.1 Movement parameters

4.3.1.1 Estimate density, D , speed, S , specific flow, F_s , effective width, W_e , and initial calculated flow F_c for each floor

In this chapter, each floor is divided in half to produce two exit calculation zones and refer to NFPA in the algorithm of evacuation time calculation [1]. It is assumed that the occupants are evenly distributed to the safety evacuation stairs, which indicated the number of the occupants at each stair is equal. For a typical floor of Taipei 101, the number of occupants is 170 as shown in Table 1. If all occupants try to move through the corridor for regular floor at the same time, that is, 85 persons moving through 37m of the 2m-wide corridor. When occupants through the corridor, the density of each floor between the 7th and 91st floor is 1.15 persons/m². With the same algorithm, the density between the ground and 6th floor is 0.27 persons/m².

The fundamental diagram of occupant movement for the relationships between densities, velocities, and flows is cited from NFPA (see Ref. [1]) as shown in Fig. 4-1. If the population density is less than 0.05 persons/ft² (0.54 persons/m²) of exit route, individuals can move at their own pace, independent of the speed of others. If the population density exceeds about 0.35 persons/ft² (3.8 persons/m²), no movement will take place until enough of the crowd has passed from the crowded area to reduce the density [1]. Between the density limits of 0.54 and 3.8 persons/m², the relationship between speed and density can be considered as a linear function and shown as [1]

$$S = k - akD \quad (4-1)$$

where S is speed (m/s) along the line of travel, D is density (persons/m²), $a = 0.266$ and $k = 1.4$ when calculating speed in meter per second and density in persons per square meter [1]. The specific flow, $F = S \times D = (1 - aD)kD$ is the flow of evacuating persons past a point in the exit route/unit of time/unit of effective width and expressed

in persons/s/m.

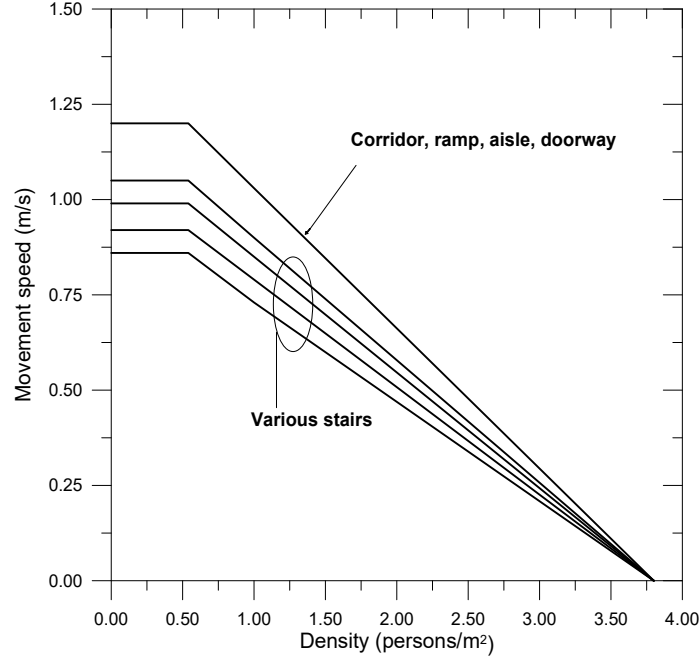


Fig. 4-1 The fundamental diagram of occupant movement [1].

Therefore, the speed is 0.97 m/s for the floor interval between the 7th and 91st floor. Between the ground and 6th floor, the density is less than 0.54 persons/m², occupants will move at their own space i.e., the speed is 1.2 m/s. Between the 7th and 91st floor, the specific flow, $F_{s(\text{corridor})}$, is $[1 - (0.266 \times 1.15)] \times 1.4 \times 1.15 = 1.12$ (persons/s/m). The specific flow is 0.32 between the ground and 6th floor. These two specific flows are less than the maximum specific flow (1.3 persons/s/m); therefore $F_{s(\text{corridor})}$ are used for the calculated flow.

According to the listing of boundary layer widths in NFPA [1], the effective width of the corridor is $2.0 - (0.15 \times 2) = 1.7$ m. The initial calculated flows for the corridor, $F_{c(\text{corridor})} (= F_s \times W_e)$, are 1.90 and 0.54 persons/s for the different interval floors, respectively.

4.3.1.2 Estimate impact of stairway entry door on exit flow

As shown in Fig. 3, each exit has a clear 1.4 m width, the effective width, W_e , is $1.4 - (0.15 \times 2) = 1.1$ m. From the equation, $F_{s(\text{exit})} = (F_{s(\text{corridor})} \times W_{e(\text{corridor})}) / W_{e(\text{exit})}$, the specific flows are 1.72 and 0.49 persons/s/m, respectively. For the door, the maximum specific flow, $F_{sm(\text{exit})}$, is 1.30 persons/s/m [1]. Since the value of $F_{sm(\text{exit})}$ between the 7th and 91st floor is less than the calculated $F_{s(\text{exit})}$, the value of $F_{sm(\text{exit})}$ is used.

Between the 7th and 91st floor, the initial calculated exit flow is $F_{c(\text{exit})} (= F_{sm(\text{exit})} \times$

$W_{e(\text{exit})} = 1.3 \times 1.1 = 1.43$ persons/s through the 1.4m width exit. Since $F_{c(\text{corridor})}$ is 1.90 whereas $F_{c(\text{exit})}$ for the single exit is 1.43, queuing is expected.

4.3.1.3 Estimate impact of stairway on exit flow

In this study, the effective width, $W_{e(\text{stair})}$ of each stairway is $1.4 \text{ m} - (0.15 \text{ m} + 0.09 \text{ m}) = 1.16 \text{ m}$. Between the 7th and 91st floor, the specific flow for the stairway $F_{s(\text{stair})}$ is $1.30 \text{ (persons/s/m)} \times 1.1 \text{ m (door)} / 1.16 \text{ m (stair)} = 1.23 \text{ persons/s/m}$. According to the riser and tread of the stair in Taipei 101, the maximum specific flow $F_{sm(\text{stair})}$ for the stairway is 0.94 persons/s/m [1]. In this case, $F_{sm(\text{stair})}$ (0.94) is less than the calculated $F_{s(\text{stair})}$ (1.23), and then $F_{sm(\text{stair})}$ 0.94 persons/s/m is used. Therefore, the calculated stair flow $F_{c(\text{stair})}$ for each stairway is limited to 1.09 persons/s (65 persons/min). Furthermore, the calculated stair flow $F_{c(\text{stair})}$ between the ground and 6th floor is 0.54 persons/s (32 persons/min).

Thus, considering that the stair flow $F_{c(\text{stair})}$ (1.09 persons/s) is relatively low when compared to the corridor flow (1.90 persons/s) calculated in the previous section. The calculated rate of queue buildup will be 0.81 persons/s. In addition, there are two landings per floor of stairway travel in this study. The maximum number of the occupants on a floor is 41. The parameters of this model are listed in Table 4-2.

Table 4-2 The parameters in the Taipei 101.

Exit route element	Parameter
Floor to floor height (7 th -91 st F)	4.2 m
Floor to floor height (Ground - 6 th F)	6.3 m
The walking speed (7 th -91 st F)	0.97 m/s
The walking speed (Ground - 6 th F)	1.2 m/s
Stair riser	20.0 cm
Stair tread	24.0 cm
Effective width of the corridor	1.7 m
Effective width of the exit, $W_{e(\text{exit})}$	1.1 m
Effective width of the stair, $W_{e(\text{stair})}$	1.16 m
The corridor specific flow, $F_{s(\text{corridor})}$	
7 th -91 st F	1.12 (persons/s/m)
Ground - 6 th F	0.32(persons/s/m)
The exit specific flow, $F_{s(\text{exit})}$	
7 th -91 st F	1.30 (persons/s/m)
Ground - 6 th F	0.49 (persons/s/m)

The exit flow, $F_{s(\text{exit})}$	
7 th -91 st F	1.43 (persons/s)
Ground - 6 th F	0.54 (persons/s)
The stair specific flow, $F_{s(\text{stair})}$	
7 th -91 st F	0.94 (persons/s/m)
Ground - 6 th F	0.47 (persons/s/m)
The stair flow $F_{c(\text{stair})}$	
7 th -91 st F	1.09 person/s (65 persons/min)
Ground - 6 th F	0.54 person/s (32 persons/min)
The maximum capacity of the stair	17 persons
The maximum capacity of the landing	24 persons

4.3.2 Evacuation modeling

Based on the occupants' movement, the calculation means of evacuation time for each stage are described as follows:

4.3.2.1 Stage 1: the occupants departing from the room and arriving at the floor exit

The evacuation time of stage 1 is obtained by dividing the distance between the floor exit and the nearest room exit by the walking speed. As mentioned previously, if all occupants try to move through the 2.0 m×37 m corridor at the same time, the walking speeds for different floor intervals are 0.97 and 1.2 m/s, respectively. Therefore, the time of stage 1 is 38 seconds for the floor interval between the 7th and 91st floor, and 31 seconds for the floor interval between the ground and 6th floor.

4.3.2.2 Stage 2: the occupants descending to the next floor

As mentioned previously, the summed flow rates of all floor exit flow in a single stairwell exceed the maximum flow rate of the stairway. The specific flows for different floor intervals are 0.94 and 0.54 persons/s/m, respectively. Using the equation $F_{s(\text{stair})} = (k - akD) \times D$, the density of the stairway flow can be calculated with $k = 1$ as follows [1],

$$0.94 = (1 - 0.266 \times D) \times D, \text{ for the } 7^{\text{th}} - 91^{\text{st}} \text{ F.} \quad (4-2a)$$

$$0.54 = (1 - 0.266 \times D) \times D, \text{ for the ground - } 6^{\text{th}} \text{ F} \quad (4-2b)$$

Therefore, the densities of the stairway flow D can be obtained and shown as approximately 1.88 and 0.65 persons/m², respectively. Thus, the speed of movement during the stairway travel is 0.50 m/s between the 7th and 91st floor. The time required

for the flow to travel one floor is $11.49/0.5 = 22.98$ seconds. After this time, the merging of flows between the flow in the stairway and the incoming flow at stairway entrances will control the rate of movement. Between the ground and 6th floor, the speed of movement during the stairway travel is 0.83 m/s. The time required for the flow to travel one floor is $17.23/0.83 = 20.76$ seconds.

After 22.98 seconds, $1.09 \times 22.98 = 25$ persons will be in the stairwell between the 7th and 91st floor from each floor feeding to it. If all floors exit all at once, there will be 1975 (except for a total 13 mechanical floors and a damper floor) persons in the single stairwell.

4.3.2.3 Stage 3: the occupants of the $n+1$ th floor merging with the crowd originally occupying the n th floor

As mentioned in Ref. [8], when the stair entry flow arrives at the lower floor and meets with the sources of exiting occupants as shown in Fig. 4-2, it is called “merge flow” (i.e. merge stage). This stage is assumed that the summed merge flow capacity of the $n+1$ th floor’s stair flow and the n th floor’s exit flow is larger than the maximum stair capacity.

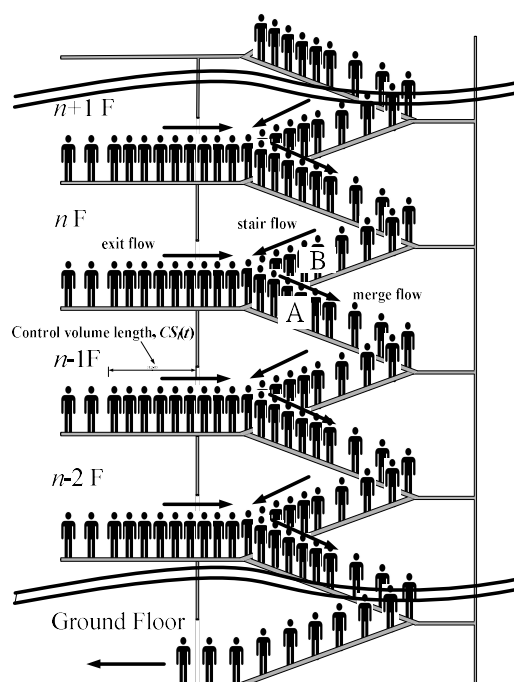


Fig. 4-2 Stage 3: merge stage [8].

The merge flow ratio R can be calculated as follows:

$$R = \dot{Q}_{n,s} / \dot{Q}_{n,e} \quad (4-3)$$

where $\dot{Q}_{n,s}$ (persons/s) is stair flow of the $n+1^{\text{th}}$ floor moving downward to the n^{th} floor, and $\dot{Q}_{n,e}$ (persons/s) is the exit flow of the n^{th} floor. When the descending flow (as mark **A** in Fig. 4-2) reaches the maximum stair capacity, the stagnation occurs (as mark **B** in Fig. 4-2) where two groups of the occupants merge. In this stage, the maximum value of the stair flow capacity is denoted as $\dot{Q}_{s(\max)}$ and the exit flow of the n^{th} floor, $\dot{Q}_{n,e}$ can be calculated as follows.

$$\dot{Q}_{n,e} = \frac{\dot{Q}_{s(\max)}}{1 + R} \quad (4-4)$$

4.3.2.4 Stage 4: the combined crowd reaching the maximum capacity of the stairwell

The simulation entered the stage 4 when the number of the occupants of a single floor approaches the floor capacity. The maximum number of the occupants in the staircase for one floor can be obtained by two components: stair landing area (m^2) multiplied by the maximum crowd density of the stair landing (people/ m^2), and stairwell area (m^2) multiplied by the maximum crowd density of the stairwell (people/ m^2). The descending flow is consisted of both stair entry flow and the outflow of the floor. When the occupants fully load the stairwell, the stair entry flow between ground floor and second floor will keep the maximum stair flow. In this stage, the relationship between the merge flow ratio (R), the stair entry flow of the n^{th} floor ($\dot{Q}_{n,s}$) and exit flow ($\dot{Q}_{n,e}$) is described as follows [8].

$$\dot{Q}_{n,s} = \dot{Q}_{s(\max)} \times \left(\frac{R}{1 + R}\right)^{n-1} \quad (4-5)$$

$$\dot{Q}_{n,e} = \dot{Q}_{n,s} \times \frac{1}{R} \quad (4-6)$$

As illustrated previously, the occupants in the control model should complete their evacuation by stairway. Though the merge flow ratio of the descending stair entry flow and exit flow for each floor is a constant, the value of stair entry flow and exit flow will vary with for different floors. It is well known that the number of occupants on each floor is the same between the 9th and 16th floors i.e. 85 occupants are assumed to use one stairwell on each floor. In addition, since occupants on each floor have the same evacuation flow speed, they will reach the exit at the same time also. After entering the stair, the time of stage 2 on each floor will be equal because of the same floor height and landing area. When the stage 3 of this evacuation model is reached, there are 25 occupants for each floor entered the stair at this time. As a consequence, there will be 60 occupants waiting in front of the exit on each floor as shown in Fig.

-3(a). Assuming the merge ratio $R=1.0$, when the occupant evacuation of the 9th floor is completed, which means that 60 occupants have entered the staircase completely, 30 and 15 occupants will simultaneously enter the staircase from the 10th and 11th floor, respectively as shown in Fig. 4-3(b). It is noted that there are mechanical floors on the 7th and 8th floor, i.e., there is no merge effect from the lower floors in the evacuation process for the 9th floor occupants.

4.3.2.5 Stage 5: the completion of the evacuation

Equations 4-5 and 4-6 demonstrate that the higher the floor the smaller the flow rate is when the value of the merge flow ratio is lower than a certain constant and the number of the stagnating occupants in the stairwell reaches the maximum. As a result, the occupants on the second floor take the lead in arriving at the ground floor. On the contrary, when the value of the merge flow ratio exceeds a certain constant value, the occupants of the roof floor take the lead in entering the stairwell [8].

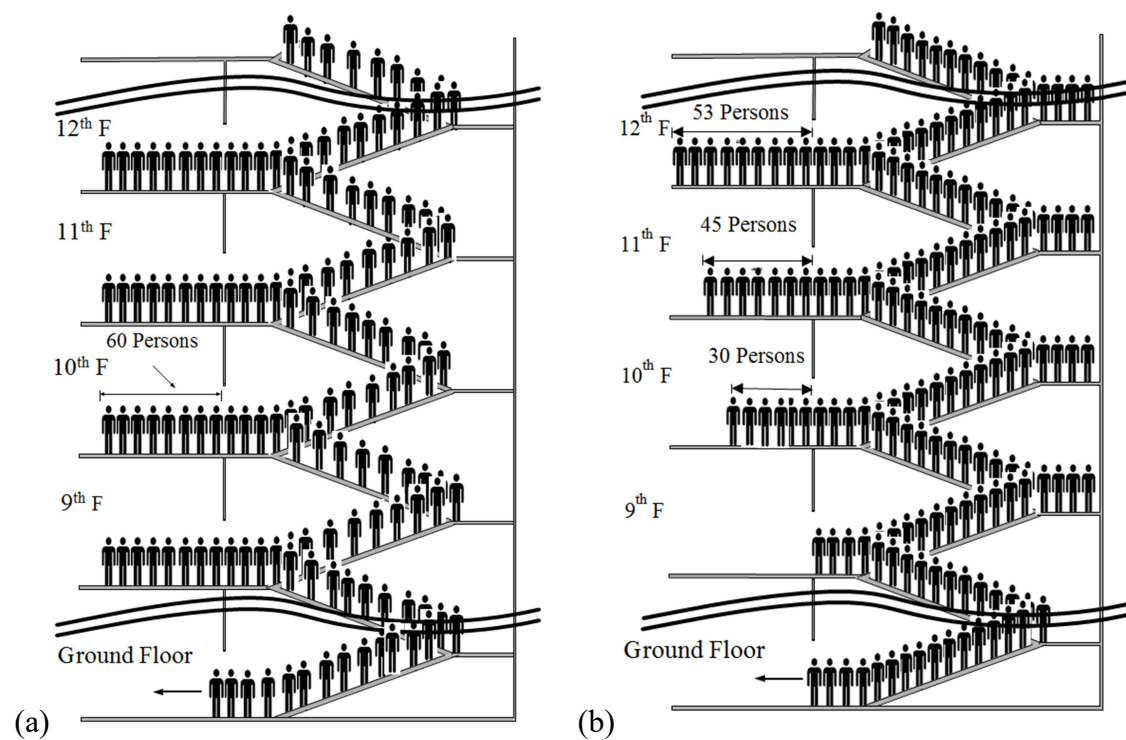


Fig. 4-3 The number of the waiting occupants at stage 3 (a) and the stagnating occupants reached the maximum (b).

4.3.3. Scenario analysis of evacuation

In the event of a fire within the office tower of Taipei 101, personnel should evacuate from office areas to pressurized corridors and further evacuate into the

emergency stairwells. On the basis of observational data of a real total evacuation drill conducted in a high-rise building, the characteristics of walking and merging behaviors of the occupants of a high-rise building descending to staircase were investigated by Yajima et al. [11]. This results showed that the merging ratio at staircase landing is nearly 1.0.

In this study, occupants are assumed to egress emergency staircases for total building evacuation and phased evacuation, and seven evacuation scenarios are presented as in Table 4-3. $R = 0.5, 1.5$ and 2.0 are used for the merge flow ratio in cases 2, 3, and 4, respectively. In a conventional way, the values of merge ratio corresponding to $R=1.0, 0.5, 1.5$, and 2.0 can be shown as 50:50, 33:66, 60:40, and 66:33, respectively to represent the ratio of the stair/exit flow. In cases 1 to 4, the parameter values of walking speed and specific flow are the same as those adopted by NFPA [1] adopted for total building evacuation. When R is equal to 1, the phased evacuation based on the initial evacuation strategies of Taipei 101 is assigned to case 5. With $R=1.0$, the walking speed and specific flow of Japan Building Center [4] are assigned to case 6, and those of Wu et al. [8, 10] are set in case 7. In case 6, the parameter values of walking speeds and specific flows are the same as those of Building Center of Japan [4] which provides the basic input for the engineering application of building facilities design in Japan. In case 7, the parameter value of walking speed in the staircase was obtained from fire drill of Taipei 101 within the 80th-1st floor i.e. 344m in height [10]. The parameter value of specific stair flow is the same as in Ref. [8], and those were obtained by analysis of videos collected of the crowd flow. It should be noted that the parameter values of cases 6 and 7 are calculated with the actual dimensions of exit and stair.

Table 4-3 The occupant behavioral parameters in the control volume model.

Scenarios	Merge flow ratio(R)	Speed $v(m/s)$	Specific flow (p/s/m)	Descriptions
Case 1	$R=1.0$ (50:50)	$v_e=1.30$	$F_{s(exit)}=1.30$ (7 th -91 st F)	The parameter values of walking speeds and specific flow are the same as NFPA [1]
Case 2	$R=0.5$ (33:66)	$v_s=0.50$ (7 th -91 st F)	$F_{s(exit)}=1.30$ (G-6 th F)	
Case 3	$R=1.5$ (60:40)	$v_s=0.83$ (G-6 th F)	$F_{s(stair)}=0.94$ (7 th -91 st F)	
Case 4	$R=2.0$ (66:33)		$F_{s(stair)}=0.47$ (G-6 th F)	
Case 5	$R=1.0$ (50:50)			Phased evacuation, the fire on the 22 nd F

Case 6	$R=1.0$ (50:50)	$v_e=1.30$ $v_s=0.783$	$F_{s(\text{exit})}=1.50$ $F_{s(\text{stair})}=1.33$	The parameter values of walking speeds and specific flows are the same as Building Center of Japan [4].
Case 7	$R=1.0$ (50:50)	$v_e=1.19$ $v_s=0.624$	$F_{s(\text{exit})}=1.12$ $F_{s(\text{stair})}=0.767$	The parameter values of walking speeds and specific flows are the same as Wu et. al. [8, 10].

As mentioned previously, total building evacuation is assumed that all building occupants are expected to evacuate at the same time to use the staircases which lead to the ground floor. However, in super high-rise buildings with large number of occupants and elevated height, total building evacuation of all occupants will result in an extensive queuing before discharge in the staircases. The exit flow is changed with the merge flow ratio during merge stage when the number of the occupants stagnating in the stairwells reaches the highest value. Furthermore, it is an empirical fact that the flow or its velocity decreases when there are people squeezing through the descending crowd.

However, there is still a lack of reliable data in relation to the times associated with particular behaviours [12]. Additionally, it is difficult to investigate the real-world merge flow ratio distribution as a large number of factors influence the evacuation and change in time scale, including the physical capabilities and psychological conditions of the occupants, the development situation of the fire, and the surrounding of the architectures [8]. Therefore, one of the main aims of this study is to analyze the different merge flow ratios and simulate the various evacuation processes.

Moreover, according to this approved fire safety evacuation plan of Taipei 101, phased evacuation is considered for the initial evacuation strategy of the fire emergency as shown in Table 4-4. For phase 1, occupants on the fire floor, the first two floors above it, and one floor below the fire floor are given a signal and message to evacuate firstly. Occupants on the third floor above the fire floor are considered as the phase 2 of the evacuees. Occupants on the second floor beneath the fire originating floor are considered as the phase 3 of the evacuees. In order to ensure life safety in the event of a fire, it is essential that the occupants be alerted with sufficient information to make a decision to move, and with sufficient time to reach a relative safety place.

Table 4-4 The priority of stairway evacuation.

Floor	Countermeasures	Priority of Stairway Evacuation
The 3 rd floor or more above floor on which fire starts	1. Evacuate by stairway. 2. Stay where you are and keep alert for further instructions 3. The starting time is beginning when all occupants of phased 1 enter the stairway.	2
The first two floors above floor on which fire starts	Evacuate by stairway.	1
The floor on which fire starts	Evacuate by stairway.	1
The floor beneath the floor on which fire starts	Evacuate by stairway.	1
The 2 nd or more beneath the floor on which fire starts	1. Evacuate by stairway. 2. Stay where you are and keep alert for further instructions 3. Evacuate by passenger elevator only if there is no fire penetrating shafts, nor initiating sprinklers nor fire hydrant operating.	3

4.4 Numerical results and discussions

4.4.1 Compare the results of the evacuation time of Taipei 101 and others

The number of prescriptive allowable occupants is 12,200 located on the floors 2 to 91 in Taipei 101. In case 1 in which R is equal to 1.0, i.e. the stair flow rate is the same as the exit flow rate and the occupants of the higher floors do not start making their escape until those of the lower floors complete evacuation. Based on the mean of control volume method evacuation calculation, the occupants of the 2nd floor are the first ones to complete evacuation (91 sec) and the occupants of the 91st floor are the last ones. The total evacuation time for 12,200 persons located from the floors 2 through 91 is estimated at 96.67 minutes (5800.3 sec). In order to compare the numerical results of this study and different evacuation literature/codes, the total evacuation times of Taipei 101 with different methods are shown in Table 4-5.

Table 4-5 The results of evacuation time for different method.

Method	Time (min)	Description
Present	96.67	1. The merge flow ratio is 1.0. 2. The parameters of walking speeds and specific flow are the same as NFPA [1].
NFPA [1]	94.4	This result is obtained by A-first order approximation.
Melinek and Booth [13]	96.2	1. There is congestion on the stairs and the occupant flow is at maximum all the time. 2. The parameters of walking speeds and specific flow are the same as NFPA [1].
Building EXODUS [14]	94.78	Designated exits are assigned.
	120.88	No person's evacuation behavior mode is designated.
Japan [4]	89.57	Verification method of evacuation safety, Route B

4.4.1.1 The first-order approximation (NFPA) [1]

As illustrated previously, if all occupants in the building start evacuation at same, each stairway can discharge 65.0 persons/min. By the mean of the first-order approximation (NFPA) [1], the persons above the first floor will require approximately 93.85 minutes to pass the exit, and an additional 0.57 min (34.5 sec.) travel time is required for the movement from the second floor from the exit. The total minimum evacuation time is estimated at 94.4 minutes (5,664 sec).

4.4.1.2 The method of Melinek and Booth [13]

According to the evacuation situations, the egress time [13] can be divided into two categories. In one case, there is congestion on the stairs and the occupant flow is at maximum all the time. In the other case, occupants can walk freely. The egress time is the maximum of these two and shown as

$$t_1 = \frac{nN}{F_s W} + t_s \quad (4-7)$$

$$t_n = \frac{N}{F_s W} + n t_s \quad (4-8)$$

where t_1 is the egress time (congestion), t_n is the egress time (free walk), n is the number of floors, N is the number of people per floor and exit, F_s is the specific flow on stairs (persons/s/m), W is the width of the stairway, and t_s is the walking time between adjacent floors (free walk). In the case of Taipei 101, congestion on the stairs is estimated and the egress time is 5771 sec (96.2 min).

4.4.1.3 Building EXODUS evacuation software [14]

Chien and Wen [14] applied the Building EXODUS evacuation software to analyze the time needed for building evacuation of Taipei 101, and a set value of software defaults is used, namely no person's evacuation behavior mode is designated. The time for the last person exiting from the first floor of the building to the exit is set at 2 hours and 52.5 seconds (120.88 min). Designated exits are assigned to all 12,000 evacuees in simulation 2 and the evacuation completion time (when the last evacuee leaves his designated exit) is set to be 1 hour and 34 minutes (94.78 min).

From Table 5, it can be seen that, with $R=1.0$ of this approach method, the total evacuation time of Taipei 101 is found to be in good agreement with the results of the NFPA first-order approximation [1], the method of Melinek and Booth [13], and EXODUS evacuation software [14] (designated exits are signed). Therefore, the analytical method in this study is reasonable.

4.4.1.4 Japan's verification method of evacuation safety [4]

In Japan, Building Standard Law (BSL) is applicable to all buildings built in which the fire regulations consist of provisions both for fire resistance and the evacuation safety of buildings. For the evacuation safety of buildings, Route B is a performance approach which is associated with the means of the verification method of evacuation safety [4]. In this approach, the total egress time can be obtained by three categories i.e. the starting time, the traveling time, and the queuing time.

Based on this means of the verification method, the starting time and traveling time can be calculated and shown as 11.68 and 23.38 minutes, respectively. Moreover, an additional 54.52 minutes queuing time is required to pass the exit. The total egress time is expected at 89.57 minutes.

4.4.2 Effect of different merge flow ratios

Simulation results for the cases 1 to 4 with evacuation time versus floor number are presented in Tables 4-6 and 4-7. Table 6 shows the time for the occupants of each floor entering the staircase, i.e. the clearance time. For the floors 2 to 6, it takes only

about 68 seconds for the occupants of each floor to enter the staircase as there is no merging and stagnation situations. Regardless of the merge flow ratio, the clearance time of the 91st floor is at 93 seconds. This is because no occupant had been assigned beneath this floor (the 90th floor) and as a consequence, the occupant movement is similar to free flow. It is interesting that from Table 6 the clearance time is at 144 seconds for the 19th floor when $R=0.5$. The main reason is that when $R=0.5$, the occupants from the 19th floor's exit flow are two times of those who come from the 20th floor's stair flow, and as a result has a smaller impact on the 19th floor's exit flow. Secondly, there are two mechanical floors beneath the 19th floor, and that provides the free movements for the occupants from the 19th floor at the initial evacuation process.

Table 4-6 The numerical results for different merge flow ratios.

Evacuation	Merge flow ratio			
	R= 0.5	R= 1.0	R= 1.5	R= 2.0
All persons on the 91 st F have evacuated	93.0	93.0	93.0	93.0
All persons on the 89 th F have evacuated	3680.3	3701.3	3712.7	3712.2
All persons on the 83 rd F have evacuated	3436.2	3462.7	3491.6	3514.1
All persons on the 81 st F have evacuated	3393.1	3405.9	3425.5	3404.0
All persons on the 75 th F have evacuated	3072.9	3099.4	3129.2	3146.2
All persons on the 73 rd F have evacuated	3029.8	3042.6	3063.1	3047.1
All persons on the 67 th F have evacuated	2709.6	2738.0	2766.8	2786.6
All persons on the 65 th F have evacuated	2666.5	2681.1	2700.8	2682.0
All persons on the 59 th F have evacuated	2346.3	2374.7	2404.4	2429.7
All persons on the 57 th F have evacuated	2303.2	2317.8	2338.4	2325.1
All persons on the 51 st F have evacuated	1983.0	2013.2	2042.0	2067.3
All persons on the 49 th F have evacuated	1939.9	1956.3	1976.0	1962.7
All persons on the 43 rd F have evacuated	1619.7	1649.9	1679.7	1707.7
All persons on the 41 st F have evacuated	1576.6	1593.0	1613.6	1603.1
All persons on the 35 th F have evacuated	1256.4	1286.6	1317.3	1345.3
All persons on the 33 rd F have evacuated	1213.3	1231.6	1251.2	1240.7
All persons on the 27 th F have evacuated	893.1	925.1	954.9	982.9
All persons on the 25 th F have evacuated	850.0	870.1	887.0	875.5
All persons on the 19 th F have evacuated	144.0	516.0	592.5	631.5
All persons on the 16 th F have evacuated	505.1	521.5	497.1	438.8
All persons on the 9 th F have evacuated	144.5	171.0	198.0	226.0
All persons on the 2 nd -6 th F have evacuated	67.8	67.8	67.8	67.8

Table 4-7 shows the times for the occupants of each floor arriving at the ground

floor. In fact, in such cases, the stair flow of cases 1 to 4 through the stair is regulated by the 65 persons/min flow rate. It can be found from the numerical results that the times for all persons evacuated the building are almost the same at 5800 seconds. Moreover, it is well known that the higher floor takes the longer evacuation time. However, when $R = 1.5$ and 2.0 (cases 3 and 4), the 89th floor is the last floor of the building to enter the stairwell and reach to the ground because of the effect of merge ratio on evacuation process.

Table 4-7 The numerical results for different merge flow ratios.

All persons on which floor have evacuated the building	Merge flow ratio			
	R= 0.5	R= 1.0	R= 1.5	R= 2.0
91 st F	5800.3	5800.2	5789.5	5785.3
89 th F	5768.2	5789.1	5800.3	5800.1
83 rd F	5386.5	5413.0	5441.8	5464.3
81 st F	5297.5	5310.2	5329.9	5345.1
75 th F	4839.7	4866.2	4896.0	4912.9
73 rd F	4750.7	4763.5	4787.0	4796.4
67 th F	4292.9	4321.3	4350.1	4369.8
65 th F	4203.9	4218.5	4238.2	4253.3
59 th F	3746.1	3774.5	3804.2	3829.5
57 th F	3657.1	3671.7	3692.3	3712.9
51 st F	3199.3	3229.5	3258.3	3283.6
49 th F	3110.4	3126.8	3146.4	3167.1
43 rd F	2652.5	2682.7	2712.5	2740.5
41 st F	2563.6	2580.0	2600.5	2623.9
35 th F	2105.8	2135.9	2166.6	2194.6
33 rd F	2016.8	2035.0	2054.7	2080.8
27 th F	1559.0	1591.0	1620.7	1648.7
25 th F	1470.0	1490.1	1507.0	1535.0
19 th F	1031.5	1047.9	1074.9	1113.9
16 th F	918.6	935.0	934.5	933.1
9 th F	397.0	424.0	451.0	479.0
2 nd F	88.6	88.6	88.6	88.6
All persons have evacuated the building	5800.3	5800.2	5800.3	5800.1

Fig. 4-4 shows the evacuation results of Taipei 101 on each floor for cases 1 to 4. The upper and lower lines represent the times of the occupants reached to the ground

and entered to stairwell from the floors 2 to 91, respectively. For each floor, the difference time between the lower line and floor axis is the clearance time; the difference time between the lower line and upper line is the time for the last occupant of each floor moving in stairway. It can be clearly seen from Fig. 4-4 that except for the points A and B correspond to the floors 15 and 16 which might be caused by some special phenomena, the moving time is nearly proportional to the floor number i.e. the higher floor takes longer time to reach the ground floor.

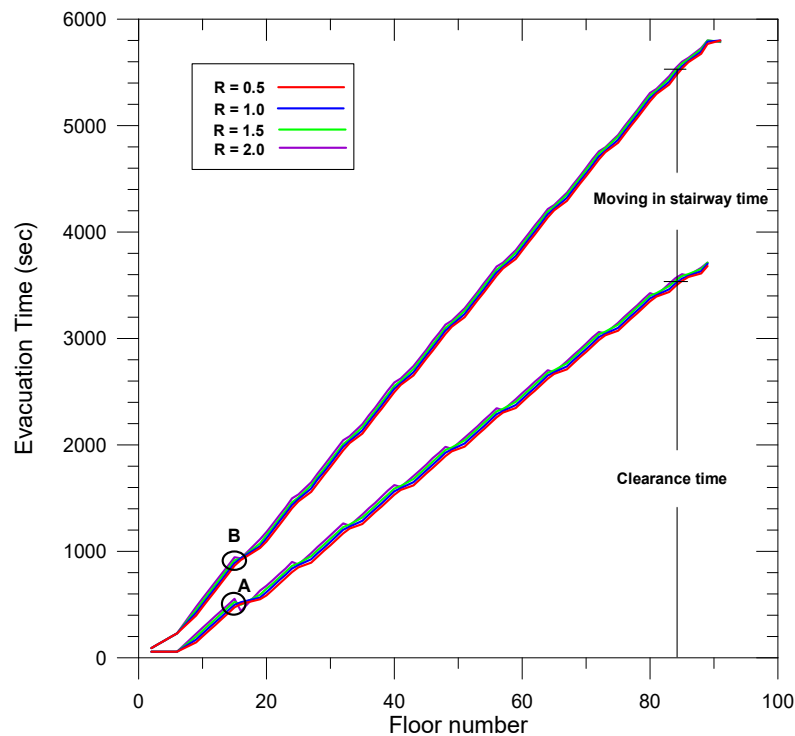


Fig. 4-4 The numerical results of the evacuation process for different merge ratios.

In order to figure out the phenomena of points A and B, Fig. 4-5 and Table 4-8 show the times of the occupants on the floors 9 to 16 entered in the stair; Fig. 4-6 and Table 4-9 show the results of the occupants evacuated the building. From the Fig. 4-5 and Table 4-8, it is easy to find that the entered time on the 16th floor is earlier than that of the 15th floor to enter the stair for $R = 1.5$ and 2.0 . Analyzing the causes of these results, the main cause is that the 17th and 18th floors are the mechanical floor, there will be no exit flow from these two floors, and which postpones the time of merging for the 16th floor's exit flow and the 19th floor's stair flow. As a result, the 16th floor's stair flow is only associated with the 16th floor's exit flow at the initial evacuation process. Moreover, after the time of merging for the stair flow from the 16th floor and the 15th floor's exit flow, the higher values of merging ratio will take the lead in entering the stairwell, as mentioned in previous. Therefore, the phenomena

are caused significantly by both the mechanical floors and the higher values of merging ratio. The similar interesting phenomenon is repeated in every 8 floors.

From Tables 4-8 and 4-9, it can be seen that that with $R=2.0$ of the occupants on the 16th floor and the 15th floor have entered the stair (i.e. clearance time) at 438.8 seconds and 553.5 seconds, respectively; the occupants on the 16th floor and the 15th floor have evacuated the building at 933.1 seconds and 944.1 seconds, respectively. It is interesting to note that though the difference of the clearance time is 115 seconds between the 16th floor and 15th floor, the difference of evacuation time for these two floors is drastically reduced. These results indicate that the merge ratio and mechanical floor have the significant effect on the evacuation process in which the occupants are engaged in the stairwell.

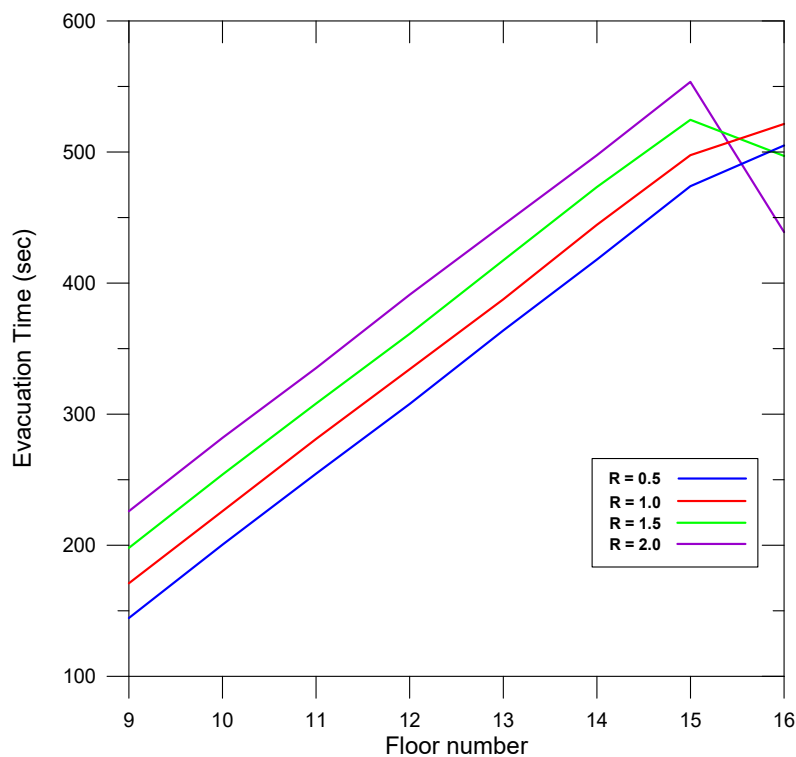


Fig. 4-5 Comparison of the evacuation times with different merge ratios.

Table 4-8 The numerical results for different merge flow ratios on Floors 9 to 16.

Evacuation	Merge flow ratio			
	R= 0.5	R= 1.0	R= 1.5	R= 2.0
All persons on the 16 th F have evacuated	505.1	521.5	497.1	438.8
All persons on the 15 th F have evacuated	473.9	497.6	524.6	553.5
All persons on the 14 th F have evacuated	417.9	444.4	473.2	497.6
All persons on the 13 th F have evacuated	363.8	387.5	417.3	444.4
All persons on the 12 th F have evacuated	307.8	334.3	361.3	391.1

All persons on the 11 th F have evacuated	254.6	281.1	308.1	335.2
All persons on the 10 th F have evacuated	200.5	226.1	254.0	282.0
All persons on the 9 th F have evacuated	144.5	171.0	198.0	226.0

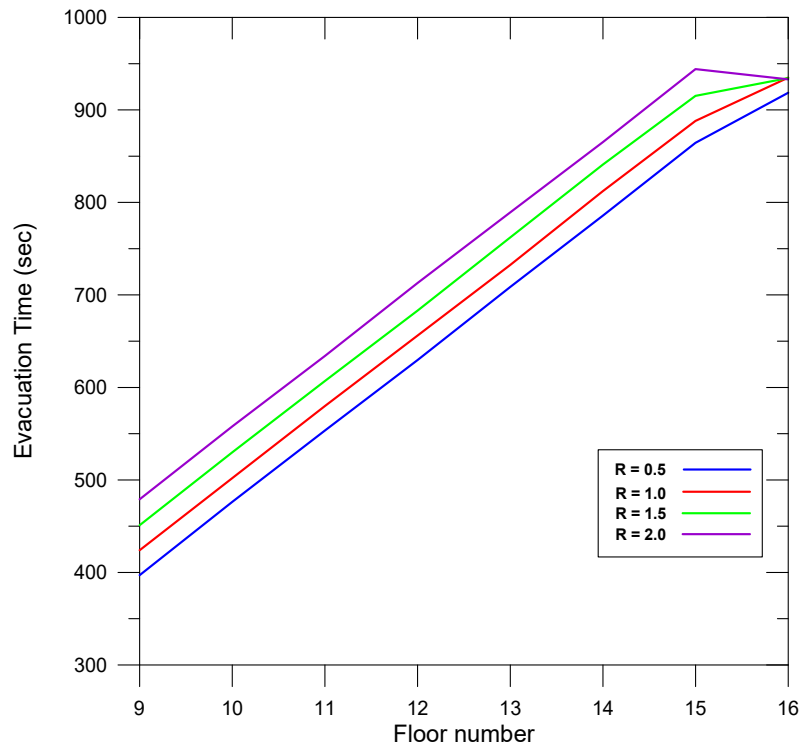


Fig. 4-6 Comparison of the evacuation times with different merge ratios.

Table 4-9 The numerical results for different merge flow ratios on Floors 9 to 16.

All persons on which floor have evacuated the building	Merge flow ratio			
	R= 0.5	R= 1.0	R= 1.5	R= 2.0
16 th F	918.6	935.0	934.5	933.1
15 th F	864.5	888.2	915.2	944.1
14 th F	785.6	812.1	840.9	865.2
13 th F	708.5	732.3	762.0	789.1
12 th F	629.6	656.1	683.1	712.9
11 th F	553.5	580.0	607.0	634.1
10 th F	476.4	502.0	530.0	557.9
9 th F	397.0	424.0	451.0	479.0

Fig. 4-7 presents the number of waiting people versus time features in the evacuation process for different merge ratios on the 9th floor. In this study, assume all occupants start to evacuate at time zero. It should be noted that the floors 7 to 8 are

mechanical floors, and there is no exit flow from these two floors. The rate of flow through the stair to the 9th floor is kept of the 65 persons/min. At 38 seconds (as point A in Fig. 4-7), occupant flow starts through the exit. $F_{c(stair)}$ through the exit is 65 persons/min for the next 23 seconds. At 61 seconds (as point B in Fig. 4-7), 25 persons are in the stairway of the 9th floor. After the time of point B, the exit flow of the 9th floor will be decided by the value of merge ratio. In Fig. 4-7, it can be easily found that the higher value of merge ratio takes the longer time for the occupants of the 9th floor to evacuate.

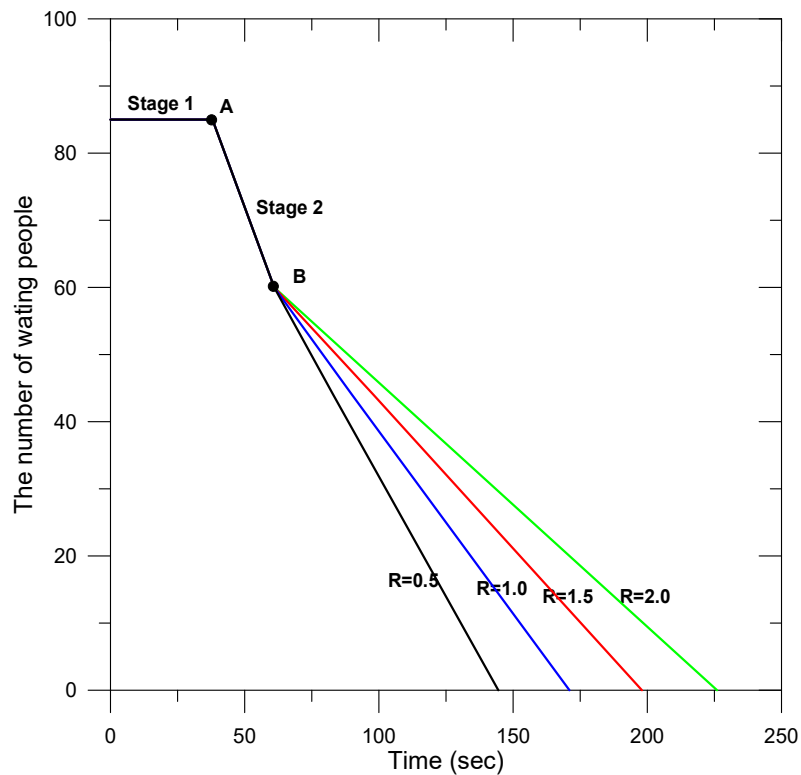


Fig. 4-7 The evacuation process of the occupants for different merge ratios on the 9th floor.

The number of waiting people versus time features for different merge ratios on the 41st floor and 75th floor are shown in Figs. 4-8 and 4-9, respectively. When the occupants reach the maximum capacity of the stairwell i.e. the stage 4 of evacuation modeling, the waiting occupants of each floor cannot enter the stairwell and become a queue in front of the exit of stairwell at this transient moment. Fig. 4-8 shows that the higher value of merge ratio obtains the less number of waiting occupants at the stage 4. At the beginning of stage 4, the number of waiting occupants on the 41st floor corresponding to $R=0.5$, 1.0, 1.5 and 2.0 is 37, 31, 29, and 26, respectively. Obviously, it is important to find the reasons for this. It should be noted that the 42nd floor is the mechanical floor, and time of merging for the 41st floor's exit flow and the 43rd floor's

stair flow will be postponed (about 46 seconds). Furthermore, when the stair flow from 41st floor merges with 40th floor's exit flow, the stair flow from the 41st floor will be larger than the 40th floor's exit flow of because of the higher values of merge ratio. Thus, when $R=2.0$, the number of waiting occupants obtains the lowest value (26 persons) on the 41st floor at the beginning of stage 4.

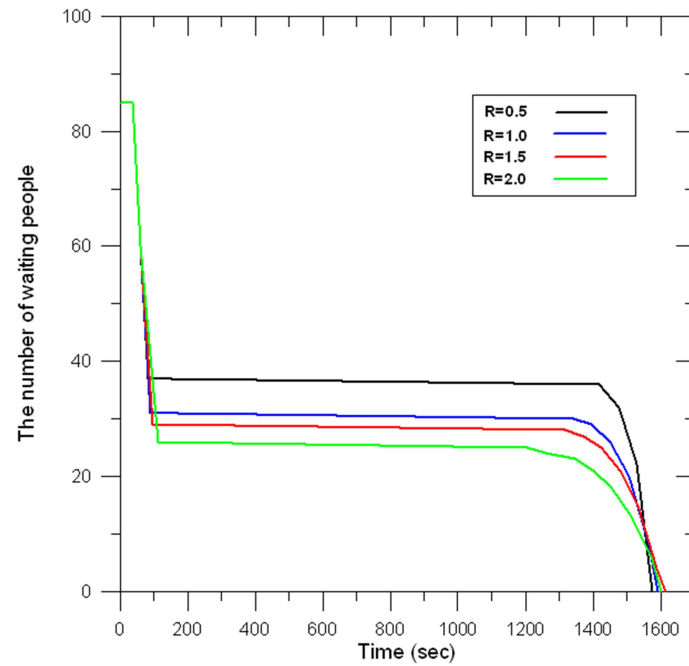


Fig. 4-8 The evacuation process of the occupants for different merge ratios on the 41st floor.

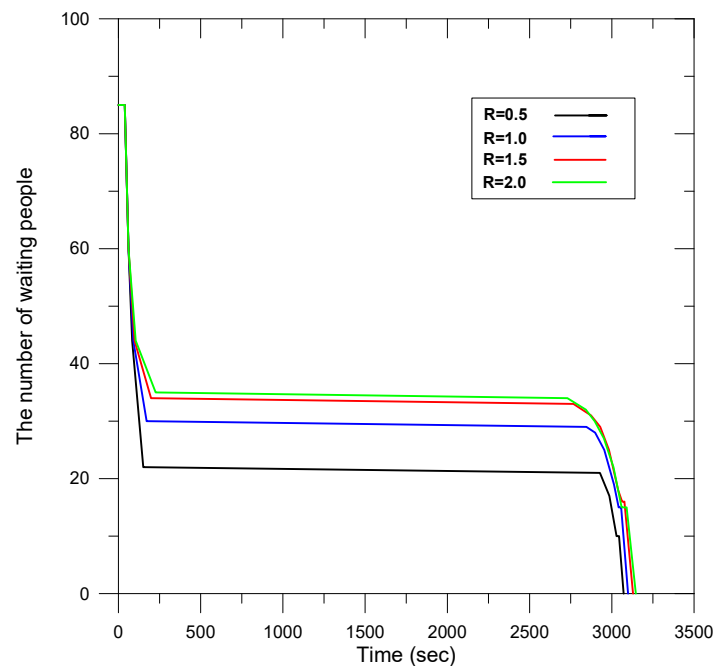


Fig. 4-9 The evacuation process of the occupants for different merge ratios on the 75th floor.

Conversely, Fig. 4-9 shows that that the higher value of merge ratio obtains the larger number of waiting occupants at this stage, the number of waiting occupants on the 75th floor corresponding to $R=0.5$, 1.0, 1.5 and 2.0 is 22, 30, 34, and 35, respectively. In this case, the 74th floor is the mechanical floor, there will be no exit flow from the 74th floor, and the exit flow of the 75th floor will take the lead in entering the stairwell for the lower value of merge ratio. Therefore, the lower value of merge ratio obtains the less number of waiting occupants on the 75th floor. As noted previously, after the time of merging the higher values of merging ratio will take the lead in entering the stairwell. This opposite feature at the stage 4 presented in Figs. 4-8 and 4-9, is caused by the mechanical floor. It is also apparent that the location of the mechanical floor and the value of the merge ratio have the dramatic influence on the evacuation process.

The number of waiting people versus the time features for different floors with $R=1.0$ is shown in Fig. 4-10. Overall, the evacuation time is proportional to the floor number, the higher floor takes longer time to enter the staircase. From Fig. 4-10, except the floors 9 and 19, the numbers of waiting people at the stage 4 on the 49th and 59th floors are clearly lower than that of the others. It should be noted that there is a mechanical floor located above the 49th floor and beneath the 59th floor, respectively. Therefore, the dynamic features of evacuation processes on the 49th and 59th floors at stage 4 are similar to the results of the 41st and 75th floors, respectively, because of the mechanical floor effect.

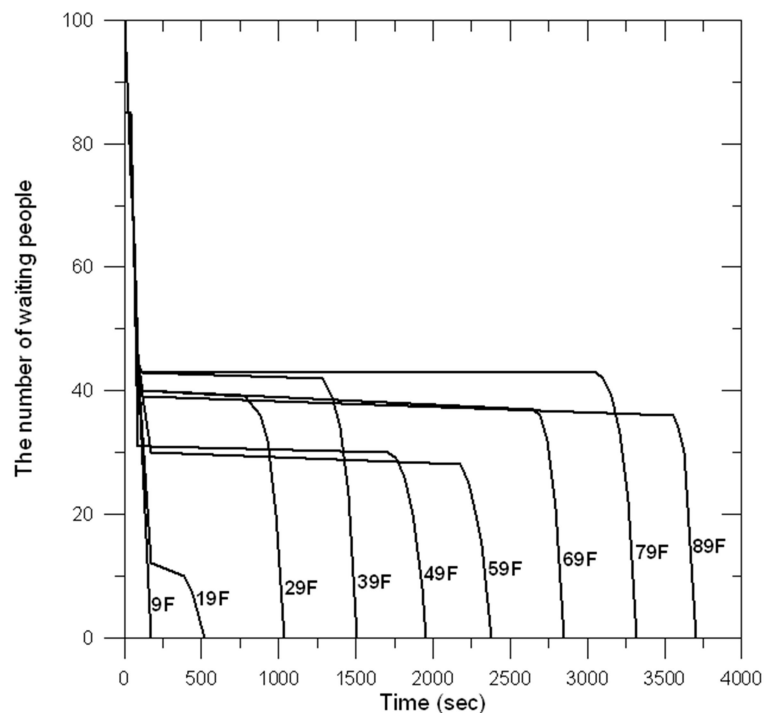


Fig. 4-10 The evacuation process of the occupants for different floors with $R=1.0$.

4.4.3 The phased evacuation

In case 5, phased evacuation is considered and the floor of fire origin is assumed on the 22nd floor. According to this approved fire safety evacuation plan of Taipei 101, the occupants on the floors 21 to 24 are the evacuees of the phase 1 to evacuate, the occupants on the floors 25 to 91 are the evacuees of the phase 2, and the occupants on the floors 2 to 20 are the evacuees of the phase 3. In this case, we analyze two scenarios to identify the evacuation times of different phases. For scenario 1, the occupant flow for each of the phased evacuation will be no merging before arriving at the ground floor. The second scenario is assumed that the phase 3 is beginning when the last one of the occupant flow of the phase 2 passes through the 21st floor. The results of the phase evacuation for different scenarios are presented in Table 4-10.

In this case, the travel distance between the ground floor and the 21st F is 264.2m and the time required for the occupant flow to the ground floor is 528.5 seconds. The number of the occupants for phases 1 to 3 is 340, 10,910, and 950, respectively. For these two scenarios, the total evacuation time of phase 1 is the same as at 878.9 seconds. For scenario 2, the activating time of phase 3 is much earlier than that of the scenario 1. In fact, there are still 576 persons in the stairwell associated with the phase 2 at the beginning of phase 3. Therefore, the total number of occupants at the beginning of the phase 3 becomes to 1526 (576+950). Since the calculated stair flow is 1.09 persons/s in this study, the required time is 1400 seconds to evacuate. For scenario 1 and 2, the total evacuation time is 6331.3 and 6170.0 seconds, respectively as shown in Table 10. These scenarios indicate that the evacuation time of the first two phases is much shorter than that of the total evacuation. The total evacuation time of case 5 is still longer than those of the cases 1 to 4.

Table 4-10 The numerical results of the phase evacuation for different scenarios

Evacuation	Phase 1	Phase 2	Phase 3
Scenario 1			
Start time	0	220.6	5260.5
All persons have evacuated	281.6	3210.4	5744.0
All persons have evacuated the building	878.9	5298.5	6331.3
Scenario 2			
Start time	0	220.6	4770.0
All persons have evacuated	281.6	3210.4	-
All persons have evacuated the building	878.9	-	6170.0

4.4.4 Effect of different walking speeds and specific flows

Tables 4-11 and 4-12 show the evacuation results of each floor for cases 1, 6, and 7 at entering the stairway and reaching the ground floor, respectively. From Tables 4-11 and 4-12, it can be easily found that the evacuation times of case 6 are much shortened as compared with the case 1. The key cause of the shortened evacuation time for case 6 could be estimated by assuming the discharge time taken for the occupants' congestion process. According to the Japan's verification method of evacuation safety [4], the calculated stair flow is obtained by the specific flow multiplying the actual width of the stairwell. In case 6, the specific flow is 1.33 persons/s/m, and thus the calculated stair flow used is 112 persons/min, which represents the calculated stair flow of case6 is not only much larger than that of NFPA (65 persons/min) but also shortens the evacuation time.

Although the values of movement parameters in case 6 are cited from Building Center of Japan [4], the numerical result of the total evacuation with the Control Volume model (i.e. 57.09 min) is not correlated well with the result of Japan's verification method (i.e. 89.57 min). In this study, the occupants are assumed to move at the same time which resulted the evacuation process shortly to reach the maximum capacity of the staircase, i.e., the stage 4 of this model. Note that the starting time and traveling time of Japan's verification method take sometimes, but the purely queuing time of Japan's method (54.52 min) is quite consistent with the result of this study (57.09 min).

Table 4-11 Comparison of the evacuation times in cases 1, 6, and 7.

Evacuation	Case 1	Case 6	Case 7
All persons on the 91 st F have evacuated	93.0	70.0	97.9
All persons on the 89 th F have evacuated	3701.3	2094.6	4133.6
All persons on the 83 rd F have evacuated	3462.7	1963.6	3858.0
All persons on the 81 st F have evacuated	3405.9	1930.3	3796.5
All persons on the 75 th F have evacuated	3099.4	1759.5	3452.0
All persons on the 73 rd F have evacuated	3042.6	1726.2	3394.3
All persons on the 67 th F have evacuated	2738.0	1555.4	3049.8
All persons on the 65 th F have evacuated	2681.1	1523.2	2988.3
All persons on the 59 th F have evacuated	2374.7	1351.3	2643.8
All persons on the 57 th F have evacuated	2317.8	1319.1	2586.1
All persons on the 51 st F have evacuated	2013.2	1148.3	2241.6
All persons on the 49 th F have evacuated	1956.3	1115.1	2180.1

All persons on the 43 rd F have evacuated	1649.9	944.2	1835.6
All persons on the 41 st F have evacuated	1593.0	910.9	1777.9
All persons on the 35 th F have evacuated	1286.6	740.1	1431.5
All persons on the 33 rd F have evacuated	1231.6	707.9	1371.9
All persons on the 27 th F have evacuated	925.1	536.1	1029.3
All persons on the 25 th F have evacuated	870.1	503.8	966.0
All persons on the 19 th F have evacuated	565.5	335.2	628.9
All persons on the 16 th F have evacuated	521.5	312.6	564.7
All persons on the 9 th F have evacuated	171.0	115.0	182.0
All persons on the 2 nd -6 th F have evacuated	55.2	48.7	60.6

Table 4-12 Comparison of the evacuation times in cases 1, 6, and 7.

All persons on which floor have evacuated the building	Case 1	Case 6	Case 7
91 st F	5800.2	3425.7	5836.8
89 th F	5789.1	3416.0	5825.7
83 rd F	5413.0	3198.0	5438.3
81 st F	5310.2	3135.7	5339.6
75 th F	4866.2	2877.9	4883.4
73 rd F	4763.5	2815.6	4788.4
67 th F	4321.3	2557.8	4332.2
65 th F	4218.5	2496.6	4233.5
59 th F	3774.5	2237.7	3777.3
57 th F	3671.7	2176.5	3682.3
51 st F	3229.5	1918.7	3226.1
49 th F	3126.8	1856.4	3127.4
43 rd F	2682.7	1598.6	2671.2
41 st F	2580.0	1536.3	2576.2
35 th F	2135.9	1278.5	2118.1
33 rd F	2035.0	1217.3	2021.3
27 th F	1591.0	958.5	1566.9
25 th F	1490.1	897.2	1466.4
19 th F	1047.9	641.6	1017.6
16 th F	935.0	575.5	897.5
9 th F	424.0	276.4	384.5
2 nd F	76.0	70.7	88.2
All persons have evacuated the building	5800.2 (96.67 min)	3425.7 (57.09 min)	5836.8 (97.28 min)

Fig. 4-11 shows the numerical results of each floor entering the stairway and reaching the ground floor for cases 1, 6, and 7. Compared with case 1, case 7 shows obviously the longer evacuation time of entering the stairway, but nearly the same time at reaching the ground floor for each floor. The entering stairway times of occupants for each floor in case 7 increase much more than those of occupants in case 1 because of the different walking stair speeds. In addition, it should be noted that the calculated stair flow of case 7 is also obtained by the specific flow multiplying the actual width of the stairwell. Therefore, the value of the calculated stair flow of case 7 (i.e. 64 persons/min) is nearly the same as that of case 1 (i.e. 65 persons/min) which results in almost the same time (about 97 mins) reaching the ground floor. Therefore, the evacuation time is highly dependent on the parameters of walking speeds and specific flows. As expected, the numerical analysis shows that as specific flow increases, evacuation time decreases.

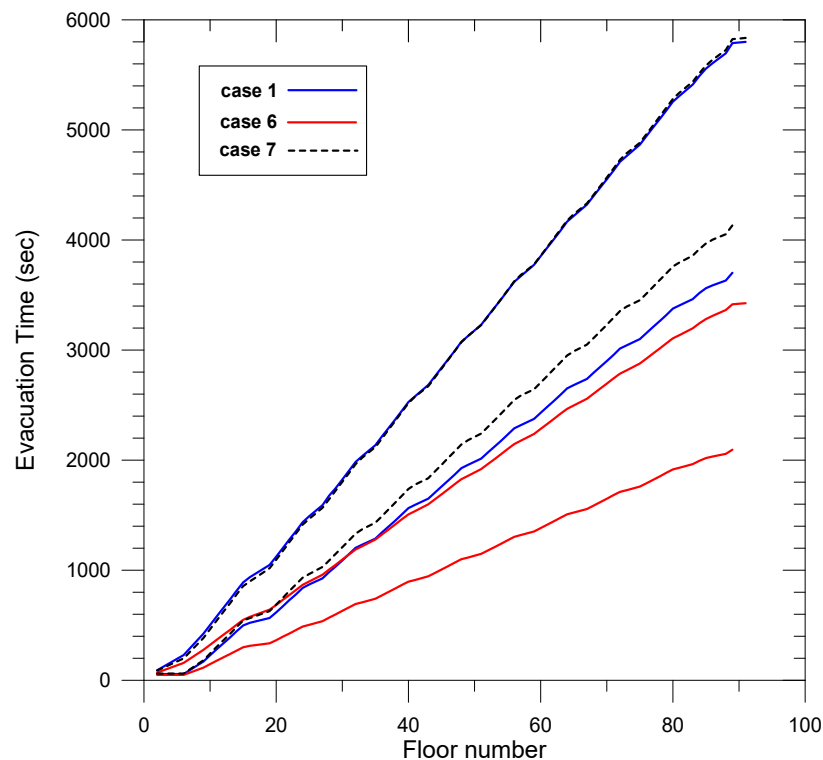


Fig. 4-11 Comparison of the evacuation times with different cases.

4.5 Conclusions of chapter

In this chapter, the results and dynamic processes of mass evacuation for total building evacuation and phased evacuation in Taipei 101 are investigated with the control volume model by performing 7 cases. Based on the on the occupants' movement, the calculation means of evacuation time are described. The total building

evacuation time of this approach method with $R=1.0$ is found to be in good agreement with the results of the NFPA first-order approximation [1], the method of Melinek and Booth [13], and EXODUS evacuation software [14] (designated exits are signed).

For total building evacuation of Taipei 101, the processes of the occupants' movement are analyzed, and it indicates that the evacuation time is nearly proportional to the floor number i.e. the higher floor takes longer time to reach the ground floor. For the cases 1 to 4, in spite the waiting occupants is significantly affected by the merge ratio during the evacuation process, the results of all occupants evacuated the building are nearly the same at about 5800 seconds because of the same value of specific stair flow. For phased evacuation (case 5), the evacuation time of the first two phases is earlier than that of the total building evacuation. However, the total evacuation time of three phases is longer than that of the case 1.

Furthermore, the evacuation processes are highly dependent on the parameters of specific flow and walking speed. With $R=1.0$, the higher value of specific flow (case 6) shortens the evacuation time significantly. With the lower value of walking speed (case 7), the entering stairway time for each floor results to increase much more than that of case 1. In this study, since the value of the calculated stair flow of case 7 is nearly the same as that of case 1, which leads to almost the same time reached the ground floor.

Using this proposed method, the effect of different merge flow ratios, walking speeds, and specific flows on the evacuation of this super high-rise building are presented and analyzed. The effect of mechanical floor on the evacuation process has been shown and discussed. Such information can then be used to work out low-risk designs for the width of exits or corridors, and the sizes of area whether people may gather and provide a wider range of possible results in the mass evacuation. Moreover, the times for the occupants of each floor entering the staircase and arriving at the ground floor are studied and specified. In this study, this proposed approach can provide new insight on the evacuation process of super high-rise buildings.

The merging behavior, pre-movement, the factors of fatigue, and counter flow are also not considered in this study. It should be noted that these results of mass evacuation cannot also represent the general features for disabled people, older people, and children. According to Low [15] a fluid particle cannot experience fear or panic, cannot have a preferred direction of motion, cannot make decisions and cannot stumble or fall. With any type of mathematical modelling we always have to be careful to distinguish between "real life" and our attempt to model it [15]. To totally understand overall emergency evacuation times for super high-rise building evacuation, the better understandings of movement and behavior of occupants for the further researches are important and needed. Particularly, more studies should be

performed to deeply look into the factors of fatigue, counter flow, the merging behaviors at the stair for mass evacuation, and the impact of disabilities on occupant movement speed and flow etc. in a staircase.

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Chapter 5

Conclusions and looking to the future

Chapter 5: Conclusions and looking to the future

5.1 Conclusions

Egress from buildings and providing for life safety during emergency events are a critical part of the building safety design. The issues of mass evacuation of super high-rise buildings have raised more attention by the general public and authorities in the world, especially since the WTC 9/11 disaster.

In this study, the literature review shown in Chapter 1 involves collecting published articles related to the topics of the evacuation process such as pre-movement time, merging behavior, evacuation simulation models, human behavior, evacuation strategy planning, egress movement etc. in high-rise/super high-rise buildings, and analyzing what can be learned through considering these collectively. By simplifying the factors of walking speed and flow coefficient, the evacuation of high-rise building is modeled with the control volume model as shown in Chapter 2. The simulation process of evacuation modelling in the stairwell of high-rise buildings is divided into 5 stages. The calculation method to obtain the fundamental characteristics of crowd movement for egress prediction is mainly referring to the method of the NFPA [1]. Based on fire drills, Chapter 3 shows the speed characteristics of mass occupants in the stairwells for various floor intervals. For mass stair movement of the super high-rise buildings, the mean speeds for vertical speed concentrate within in a range from 0.22~0.24 m/s and the walking speeds are within 0.61~0.65 m/s. This data is in good agreement with the studies by Ma et al. [2] and Kadokura [3].

Chapter 4 provides the results and dynamic processes of mass evacuation for total building evacuation and phased evacuation in Taipei 101 with control volume model. Based on the fundamental diagram of occupant movement and the algorithm of evacuation time calculation of NFPA [1], the fundamental characteristics of crowd movements such as density, walking speed, stair flow, specific flow, etc. are estimated. The effects of different walking speed, coefficient of flow rate, and merge flow ratio on the dynamic change and the number of the occupants stagnating for each floor in various time scales are investigated and analyzed. The conclusions of this study are summarized as follows:

1. The total building evacuation time of this approach method with $R=1.0$ is found to be in good agreement with the results of the NFPA first-order approximation [1], the method of Melinek and Booth [4], and EXODUS evacuation software [5] (designated exits are signed).
2. For total building evacuation of Taipei 101, it indicates that the evacuation time is nearly proportional to the floor number, i.e. the higher floor takes longer time to

reach the ground floor. For the cases of the total building evacuation, the higher values of merging ratio will take the lead in entering the stairwell. In spite the waiting occupants are significantly affected by the merge ratio during the evacuation process, the results of all occupants evacuated the building are nearly the same at about 5800 seconds because of the same value of specific stair flow.

3. The evacuation processes are highly dependent on the parameters of specific flow and walking speed. With $R=1.0$, the higher value of specific flow shortens the evacuation time significantly. With the lower value of walking speed, the entering stairway time for each floor results to increase much more than that of the higher value of walking speed.
4. For phased evacuation, the evacuation time of the first two phases is earlier than that of the total building evacuation. However, the total evacuation time of three phases is longer than that of the total building evacuation.
5. The effect of mechanical floor on the evacuation process has been shown and discussed in this study. This opposite feature at the stage 4 of the evacuation process presented in Figs. 4-8 and 4-9, is caused by the mechanical floor. It is also apparent that the location of the mechanical floor and the value of the merge ratio have the dramatic influence on the evacuation process.
6. The merging behavior, pre-movement, the factors of fatigue, and counter flow are not considered in this study. These results of mass evacuation cannot also represent the general features for disabled people, older people, and children.

In this study, the control volume model assumes that each occupant is an independent individual. During evacuation process, when the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface (control surface) is formed by connecting the occupants at the exit and that is changed with time. The closed surface is changed with time and the summation of different rate between the inflow and outflow. By setting the height of each individual as 1, the area of the closed surface is equal to the control volume, thus, the closed surface is called the control surface. In addition, the evacuee flow is assumed as homogeneous, which means the evacuees walk with the same velocity, the evacuee flow from the door or exit is continuous, thus the specific flow is a constant.

Using this proposed method, the effect of different merge flow ratios, walking speeds, and specific flows on the evacuation of this super high-rise building are presented. Such information can then be used to work out low-risk designs for the width of exits or corridors, and the sizes of area whether people may gather and provide a wider range of possible results in the mass evacuation. Moreover, the times for the occupants of each floor entering the staircase and arriving at the ground floor are studied and specified. In this study, this proposed approach can provide new

insight on the evacuation process of super high-rise building.

5.2 Looking to the future

As mentioned in Chapter 1 and discussed in Chapter 2, many theoretical models and numerical programs have been established for studying the effect of human behaviors on the evacuation performance. In general, the evacuation performance depends on the human behaviors, crowd flow velocity, crowd density, physical factors of architectures, and his interaction with the others in the crowd. However, with any type of mathematical modelling we always have to be careful to distinguish between “real life” and our attempt to model it. A fluid particle cannot experience fear or panic, cannot have a preferred direction of motion, cannot make decisions and cannot stumble or fall [6]. Furthermore, with the development of modern technologies and design concepts, many researches have converged to raise the viability of the use of elevators during emergencies and suggested that if enhancements are provided to the elevator system [7-10].

In order to improve the evacuation modelling of super high-rise buildings during a real or perceived event, there are some suggestions to be considered in the future works as follows.

1. Build a multi-pattern model for investigating the total egress time

The study could serve as a numerical method for building management authorities to get a better insight on the possible effects and provide quantitative information during the evacuation processes. However, the pre-movement time-lag, alarming response, and broadcasting response are not considered in this study. The evacuee flow from the door or exit is continuous, the specific flow is a constant, and all occupants start egress at the same time. In addition, most of the previous studies established the relations between the occupant pre-movement reactions and the behavior patterns, but the evacuation simulation model to determine both the pre-movement response time and the coefficient of flow rate or walking speeds transient changed during evacuation processes is limited. One of the future works is to build a multi-pattern model for investigating the reasonable total egress time with the occupant pre-movement responses and some effects of real life under fire.

2. Improve the characteristics of occupant movement during evacuation processes

The characteristics of pedestrian movement in the stairs of super high-rise buildings may cause the phenomena of congestion and bottleneck, influence the total evacuation time and the safety of evacuees. The empirical relation between density and velocity of pedestrian movement is not completely analyzed, particularly with regard to the ‘microscopic’ causes which determine the relation at medium and high densities [11].

In addition, for most experimental scenarios, the emotional situation of the participants is relaxed, two-dimensional effects can certainly not be disregarded, so some effects of real life will not be shown. Moreover, It is well known that the speeds of participants from upstairs are reduced by the entry of participants from the corresponding floors during the merging time period.

To totally understand overall exit times for super high-rise building evacuation, the better understandings of movement and behavior of occupants for the further works are important and needed, particularly with various stair widths and the ratios of tread and riser, the factors of fatigue, the congestion conditions at each room, the merging behaviors at the stair for mass evacuation, and the impact for disabilities on occupant movement speed and flow etc. in a stairwell.

3. Combine elevator-assisted evacuation

For egress strategies: from total evacuation to protect-in-place strategies, with numerous options in between. An appropriate egress strategy requires a good understanding of the buildings, its occupants, the protection measures in place, and the expected emergency responses [12]. As mentioned in Chapter 1, the elevators in super high-rise buildings to assist total evacuation appear to be promising in improving evacuation efficiency. However, using elevators to move all occupants to ground safety point may not be an optimal solution [13]. When the elevator is considered to assist the evacuation of buildings, the future work of simulation model should be carefully combined with the egress strategies, the characteristics of occupant movement, the percentage of occupants choosing stairs, and the parameters of elevator. Then, it would be valuable to provide a complete evacuation modelling to all possible occupant movement behaviors and elevator dispatching strategies during emergency events, with which the evacuation of super high-rise buildings can be completely simulated and investigated more really.

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Appendix

*Modeling the occupant evacuation of the Mass Rapid
Transit Station using the control volume model*

Appendix

Modeling the occupant evacuation of the Mass Rapid Transit Station using the control volume model

A1. Introduction of appendix

In this appendix, a control volume model is applied to simulate the process of evacuation in mass rapid transit (MRT) station using different scenarios. The control volume model assumes that each individual is an independent particle. When the evacuation occupant flow is larger than the capacity of the exit so that a virtual closed surface called the control surface that can be formed by connecting the waiting occupants at the exit. The change of the control volume is dependent on the transient number of the waiting occupants only. Based on the homogeneous flow with neglecting the behavior of the individual, the dynamic change of the evacuation occupant at the exit of the platform and the concourse can be formulated and analyzed. In addition, the number and capacity of the exits used in the total evacuation time analysis were measured with the aid of video recording and on-site observations. Using the control volume model, the dynamic characteristics of the evacuation process at each time-step for each of the exits are calculated and discussed. Comparisons are also made with the results found from other studies and NFPA 130.

A2. The control volume model

A2.1 Physical Assumptions

In this appendix, the control volume model assumes that each individual passenger is an independent particle. When the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface is formed by connecting the particles at the exit. The control volume model is applied to the platform as shown in Fig. A-1 with the passengers moving from the carriages to the platform level and then to the exits. The closed surface is changed with time and the summation of different rate between the inflow and outflow. By setting the height of the particle (each individual) as 1, the area of the closed surface is equal to the control volume, thus, the closed surface is called the control surface.

Therefore, the change of particle number in the control volume can be determined by deducting the number of the outflow particles from the inflow ones. Assuming the particle number per unit area as a constant, the transient area of the control volume can be easily derived from particle number within the control volume. The physical

assumptions of the control volume model are as follows:

1. The control volume method is based on the homogeneous flow neglecting the behavior of the individual passenger. The crowd moves at the same speed as the individual.
2. Under the circumstance of a constant passenger flow per unit width at the exit, flow is equal to speed multiplies the density and width.
3. The crowd moves following the pre-defined routes, there is no separation of the crowd.
4. In case of stagnation, the particle number per unit area remains constant.
5. The conditions of various exits are the same. All of the passengers are divided into groups nearly in proportion to the exit capacities provided by various routes on the platform.
6. The pre-movement time-lag, alarming response, and broadcasting response are not considered.

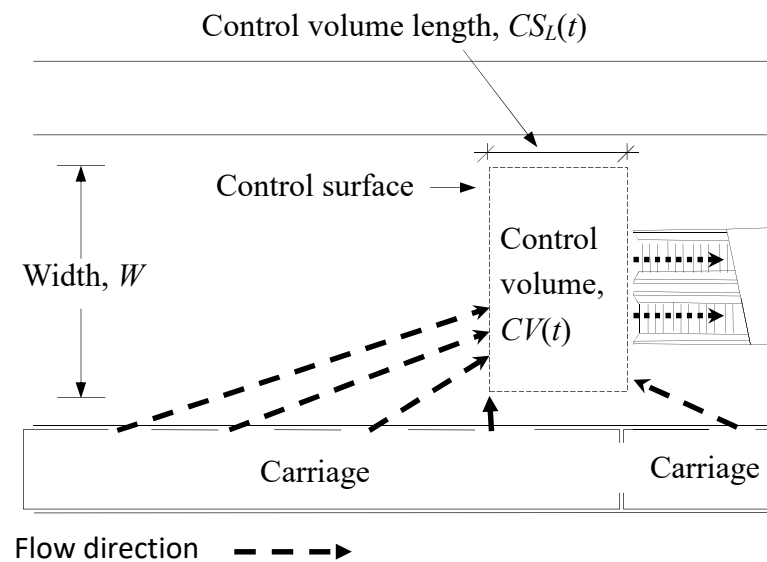


Fig. A-1 Control volume model.

Under the above assumptions, the application of the control volume model to the station evacuation is influenced by many factors, including the number of passengers in the carriage, the flow rate of the carriage doorways, the crowd velocity, the distance of the carriage to the emergency exits, the flow rate of the emergency exits, and the number of people waiting on the platform. The change of passengers in the control volume can be obtained from the above-mentioned factors.

A2.2 Calculation procedures

The formula for calculating the control volume is shown below. It is assumed that

there are independent outflows from various doorway exits during the evacuation with the starting time of the doorway exit is when the first passenger arrives at the control surface and the ending time is when the last passenger arrives at the control surface. Therefore, the initial and ending time of the Nth doorway exit to the control surface is defined as follows:

$$T(N): T_0(N) \leq t \leq T_0(N) + TP/(\dot{Q}_1 \times W_1 / 60) \quad (A1)$$

where $T_0(N)$ is the initial time when the first passenger of the Nth doorway exit to reach the control surface (sec), TP is the amount of people who flow through a certain doorway exit, \dot{Q}_1 is the capacity of carriage door (people/mm-min), W_1 is the width of the doorway exit (m). It can be seen from the above assumptions that $T_i(N) + TP/(\dot{Q}_1 \times W_1 / 60)$ represents the time when the last passenger of the Nth carriage reaches the control surface. To obtain $T_0(N)$, the distance between the first passenger of the Nth carriage at certain time point t and the control surface can be written as follows:

$$D_N(t) = [D_N(0) - CS_L(t)] - V \times t \quad (A2)$$

where V is the velocity of the crowd move (m/s), $D_N(0)$ is the distance between the initial distance ($t = 0$) and the doorway exit (m), $CS_L(t)$ is the length of the control volume(m). Hence the condition $D_N(t) = 0$ is the solution of the $T_0(N)$ in the Eq. (A1) and there is no distance between the first passenger of the Nth doorway exit and control surface.

The second part of the calculation is to obtain the number of people stagnating at the exits at certain time point t . From Eq. (A1), the flow rate of the passengers, $\dot{Q}_N(t)$, at the Nth carriage doorway exit moving to the control volume can be described as follows:

$$\dot{Q}_N(t) = \begin{cases} 0, & t < T_0(N) \\ \dot{Q}_1 \times W_1, & T_0(N) \leq t \leq T_0(N) + TP/(\dot{Q}_1 \times W_1) \\ 0, & t > T_0(N) + TP/(\dot{Q}_1 \times W_1) \end{cases} \quad (A3)$$

The flow rate of the passengers moving toward the staircases or the exits can be formulated as

$$\dot{Q}_{out} = \dot{Q}_2 \times W_2 \quad (A4)$$

where \dot{Q}_2 is the flow rate of the exit (people/m.s) and W_2 is the width of the exit (m). Combining Eq. (A3) and Eq. (A4), the total number of passengers flowing to the control volume at the certain time point t is presented as follows:

$$Q_{total}(t) = \sum_{N=1}^M (\dot{Q}_N(t) \times t) + TR - \dot{Q}_{out} \times t \quad (A5)$$

where TR is the number of passengers waiting on the platform (people).

If $Q_{total}(t)$ is less than 0, there are more passengers flowing in than flowing out of the exit with no stagnation. When stagnation occurs, the number of passengers per unit area is constant. Therefore, the size of the control volume at the certain time point t can be formulated as below:

$$CV(t) = Q_{total}(t) / PA \quad (A6)$$

where $CV(t)$ is the value of the control volume at certain time point t (m^2), PA is the number of passengers accommodated per unit area (people/ m^2).

The length $CS_L(t)$ of the control volume at certain time point t can be derived as:

$$CS_L(t) = CV(t) / W \quad (A7)$$

where W is the effective width of the platform level (m). It is worth mentioning that the effective width of the platform level is not equal to its actual width as passengers tend to flock around the exits.

A3. The statistics of the occupant flow

In this research, Gon-Guang station is chosen for its standard design of platform levels and concourse levels. The layout of each level, escalators, stairs and exits are shown in figures A-2 and A-3. On the platform level, there are three escalators, two running upward and one downward. Three stairs at each exit, one emergency stair is provided at each end of the platform. The concourse level has two paid areas separated from the outside; one fare array contains 5 electronic fare gates and 1 service/handicapped gate and the other array containing 6 electronic fare gates and 1 service/handicapped gate. The input of the calculation in this research uses the pre-defined occupant load when the station was designed.

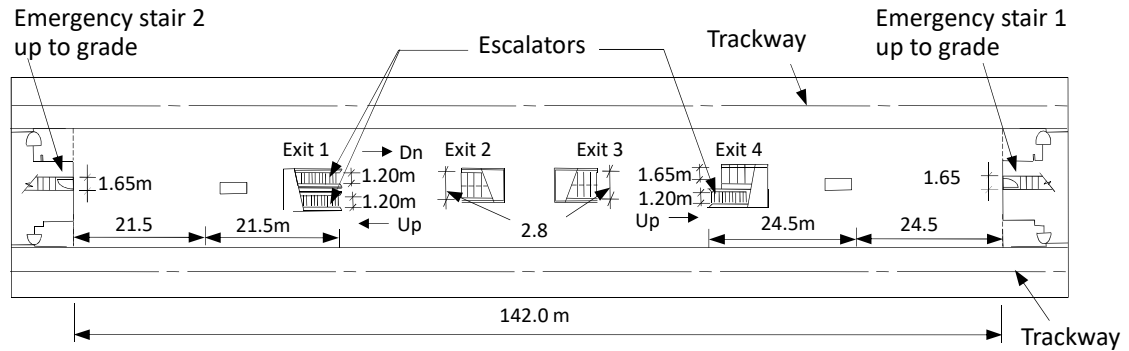


Fig. A-2 The platform level.

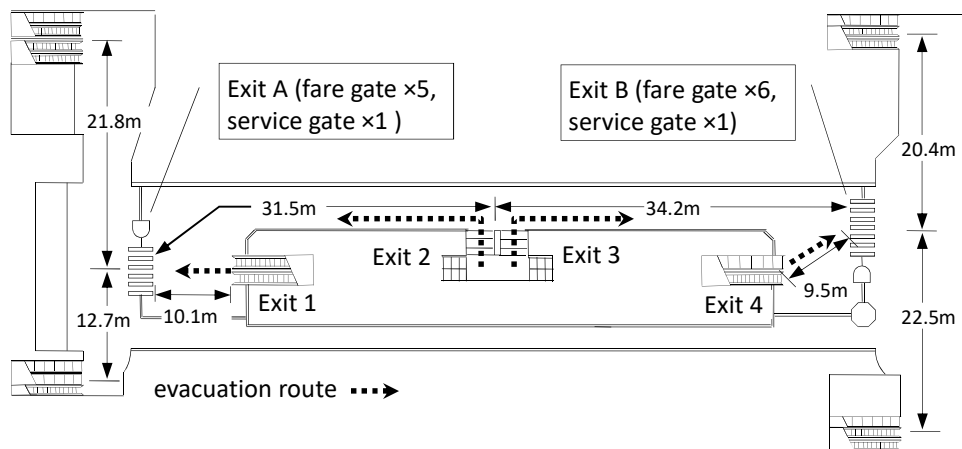


Fig. A-3 The concourse level.

It is worth mentioning that the design of Taipei City Metro Stations is based on NFPA130 code [A1]. In this study, the occupant characteristic is obtained by using NFPA 130 parameters and collecting statistics by recording the occupant flow in the adjacent stations during the 2007/2008 New Year party and the Lantern Festival. As there were so many passengers in the station, the objectives of the measurement are to understand the crowding conditions, to extract relevant data for evacuation simulation, and to justify the simulated results. The statistics of the occupant flow are shown in Table 1 and the procedures of the measurement are briefly explained as follows:

1. All numbers and capacities of the exits were measured more than 20 times.
2. On-site counting and recording was done concurrently and the one minute of the most intensity was sampled.
3. The escalator and the stair are 1.22m and 1.65m wide, respectively. When the train arrived at the station, the larger number of the occupant passing the fare gates was sampled.
4. The psychological characteristics of the occupant behavior were not taken into consideration.

From Table A-1, it is seen that the average capacity of the escalators (p/mm-min) is approximately two times that of the stairs. Compared to NFPA130, the capacity of the escalators is larger by 48.6% and the stairs is smaller by 22.9%. The on-site observation shows that the occupants preferred escalators than stairs during non-evacuation times, which resulted in the higher usage of the escalators. In addition, the average capacity of the fare gates is 38 people per minute, which is 24% lower than the NFPA 130 parameters - 50ppm. The average capacity of the service gates is 0.0573ppm, which is a 30% decrease compared to the NFPA 130 parameter - 0.0819ppm. What caused the decrease in the average capacity of the fare gates is that occupants are required to present their tickets at the fare gates during the non-evacuation time while they are allowed to pass through the fare gate during the evacuation.

Table A-1 Egress analysis of Gon-Guan station

Egress element	mm	p/mm-min		
		NFPA 130 [A1]	Investigated data	
<i>Platform to concourse</i>			Max.	Avg.
Stairs (3)	7250	0.0555	0.0460	0.0428
Escalators (2*)	2440	0.0555	0.0920	0.0825
Emergency stairs (2)	3300	0.0555	0.0460	0.0428
<i>Through far barriers</i>				
Fare gates (11), capacity(p/min)		50	48	38
Service gate (2)	2440	0.0819	0.0672	0.0573
<i>Fare barriers to safe area</i>				
Stairs (5)	8250	0.0555	0.0460	0.0428
Escalators (8)	9760	0.0555	0.0920	0.0825
Walking time for the longest exit route	m	m/min		min
<i>Platform to safe area</i>				
On platform, T ₁	24.5	61.0		0.40
Platform to concourse(vertical distance), T ₂	4.44	14.6		0.30
On concourse, T ₃	56.7	61.0		0.93
Concourse to grade(vertical distance), T ₄	8.5	14.6		0.58
Total walking time, T=T ₁ +T ₂ +T ₃ +T ₄				2.22

* one escalator discounted

A4. The results of evacuation time based on NFPA 130

In NFPA 130, the total evacuation time is the sum of walking time consumed in the longest route and the waiting time at various circulation elements. In addition, the evacuation time for an underground station should meet two requirements: (1) evacuating occupants on the platform in 4 minutes or less (2) evacuating occupants at the most remote point of the platform to the safety point in 6 minutes or less.

It is well known that the occupant load is composed two parts, the entraining load and the calculated train load. In this study, in order to calculate the evacuation time we considered two scenarios:

Scenario 1: the occupant load is 2245 persons, which is the basis on which Taipei Metro Transit system was designed where the maximum entraining load awaiting a train is 325 persons, and the calculated train load is 1920 persons as used for the most passengers capable of occupying a train.

Scenario 2: the occupant load is 4425 persons. The train load is considered that trains arrive at one platform from the peak and off-peak directions simultaneously. In addition, the entraining load for the peak direction and off-peak direction is computed as described in NFPA130.

According to the calculation of egress requirement specified in NFPA130, one of the escalators on the platform at each station shall be considered as being out of service, and escalators running toward the egress shall remain in operation. In this study, the escalator running opposite to the direction of the egress in Exit 4 is considered out of service, and the escalator in Exit 4 shall be capable of being stopped remotely. Based on the means of NFPA130 Annex C, the results of evacuation time for these two scenarios with different capacities of the exits are shown in Table A-2.

In the above calculation, all parameters input to Scenario 1 yield satisfactory results which meets NFPA test requirement while Scenario 2 does not. As a result, occupant load is the most important factor affecting evacuation time for existing stations. The responding strategies are crucial in Taipei Metro Station management such as controlling the number of the trains entering the station or trains bypassing the stations in case of fire emergency.

Table A-2 The results of evacuation time with NFPA 130 for different scenarios (minutes)

Type of parameters	Scenario 1			Scenario 2		
	NFPA 130	Investigated data		NFPA 130	Investigated data	
	[A1]	Max.	Avg.	[A1]	Max.	Avg.
Test No. 1 (≤4 mins)	3.11	3.43	3.71	6.14	6.77	7.32
Test No. 2	4.93	5.25	5.53	7.96	8.59	9.14

A5. Numerical results and discussions based on control volume model

A5.1 Event tree analysis

As mentioned in section 4, there are two scenarios. The event tree analysis for evacuation time using the control volume model is shown as in Fig. A-4.

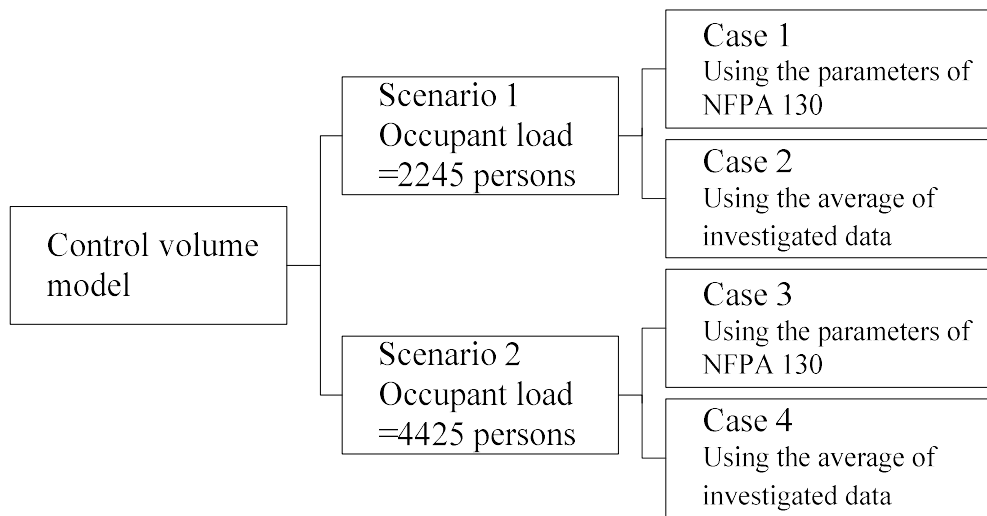


Fig. A-4 Event tree analysis for evacuation time.

A5.2 Occupant distribution on platform

When an emergency occurs, the passengers waiting on the platform and embarking on the train (namely occupant load) evacuate toward four exits on the platform level and emergency exits on each side. It is noted that the train load is 1920 persons. There are six carriages in each train and roughly 320 persons per carriage. There are four doorways in each carriage and 80 persons flow through each doorway on an average basis. Without taking evacuation behavior and guidance into consideration, it is assumed that all passengers divide into groups nearly in proportion to the exit capacity provided by various routes on the platform. It is also assumed that passengers, once having decided an escape route, will stay on that path until evacuation is achieved.

While the total number of passengers evacuating through each individual exit remains unchanged, the number of awaiting passengers is adjusted to accord with the exit capacity itself. The basic condition of evacuating all passengers on the platform level simultaneously is also satisfied. The occupant distribution for Case 1 to 4 is

shown in Tables A-3 and A-4. The gate capacity is presented as people per minute (ppm) in this section.

In addition, all passengers who flow through Exit 1 and Exit 2 use Exit A on the concourse level; and all passengers who flow through Exit 2 and Exit 3 use Exit B on the concourse level. The above assumption applies to all case calculations. The exit capacity analysis of the sample station is shown in Table A-5.

As shown in Table A-5, for Case 1 and 3 the exit capacity of either Exit A or Exit B (fare barrier exit) is greater than the combined capacity of Exit 1 and Exit 2. It is also greater than the sum of Exit 3 and Exit 4 capacities. The outcome explains that the waiting time at the fare barriers is 0. However, for Case 2 and 4, the fare barrier exit capacity of Exit A is smaller than the combined capacity of Exit 1 and Exit 2. This means that the waiting time at the fare barrier needs to be considered for Case 2 and 4.

Table A-3 The occupant distribution for the Scenario 1

Exit	Width (Mm)	Capacity (ppm)		Carriage passengers		Waiting passengers		Number of people		% of people	
		NFPA 130 [A1]	Present data	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Emergency stair 1	1650	92	71	240	240	45	23	285	263	12.70	11.72
Exit 1	2440	135	153	400	480	22	86	422	566	18.78	25.25
Exit 2	2800	155	120	400	360	84	85	484	445	21.56	19.80
Exit 3	2800	155	120	400	360	84	85	484	445	21.56	19.80
Exit 4	1650	92	71	240	240	45	23	285	263	12.70	11.72
Emergency stair 2	1650	92	71	240	240	45	23	285	263	12.70	11.72
Total		721	606	1920	1920	325	325	2245	2245	100.00	100.00

Table A-4 The occupant distribution for the Scenario 2

Exit	Carriage passengers		Waiting passengers		Number of passengers		% of passengers	
	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4
Emergency stair 1	480	400	82	119	562	519	12.70	11.72
Exit 1	720	1040	111	78	831	1118	18.78	25.26
Exit 2	840	800	114	75	954	876	21.56	19.79

Exit 3	840	800	114	75	954	876	21.56	19.79
Exit 4	480	400	82	119	562	519	12.70	11.72
Emergency stair 2	480	400	82	119	562	519	12.70	11.72
Total	3840	3840	585	585	4425	4425	100.00	100.00

Table A-5 The exit capacity analysis of the sample station (ppm)

Exit	Cases 1, 3	Cases 2, 4
<i>Platform level</i>		
Exit 1	135	153
Exit 2	155	120
Exit 3	155	120
Exit 4	92	71
<i>concourse level (throughfare barriers)</i>		
Exit A	350	260
Exit B	400	298

A5.3 Walking time

The walking time between various exits and safety points using control volume model is shown in Table A-6. The walking time to the platform is measured by the distance between the carriage and the exit. As a result, the time required for evacuation to the exit shall consider both the vertical distance of the platform to concourse and horizontal distance of the fare barrier to the safety point.

Table A-6 The walking time for exit route

	Distance (m)	Velocity (m/min)	Time (min)
Platform to concourse (vertical distance)	4.44	14.6	0.30
On concourse			
Exit 1 to Exit A	10.1	61.0	0.17
Exit 2 to Exit A	31.5	61.0	0.52
Exit 3 to Exit B	34.2	61.0	0.56
Exit 4 to Exit B	9.5	61.0	0.16
Exit A to grade			
(horizontal distance)	21.8	61.0	0.36
(vertical distance)	8.5	14.6	0.58
Exit B to grade			

(horizontal distance)	22.5	61.0	0.37
(vertical distance)	8.5	14.6	0.58

A5.4 Statistics in different scenarios

In this study, the capacity of each egress element is based on the NFPA 130, the parameters of the exits are summarized in Table 1, and others are explained as below:

$$\dot{Q}_1 = 0.0893 \text{ p/mm-min}, W_1 = 1500 \text{ mm}, V = 1.02 \text{ m/s}, PA = 4.0 \text{ (people/m}^2\text{)},$$

$$TP = 80, W = 6.0 \text{ m}, TR = \begin{cases} 325, & \text{for scenario 1} \\ 585, & \text{for scenario 2} \end{cases}$$

Please note that the occupants in the platform level rush directly to various exits in case of emergency; the occupant distribution is shown in Tables A-4 and A-5. While \dot{Q}_1 is equal to 0.0893 p/mm-min, it roughly takes 35.84 seconds for the passengers in the carriage to achieve complete evacuation.

Based on the control volume model, Figure A-5 shows the dynamic changes in the number of waiting occupants in each platform exit for Case 1. It is seen that the curves can be divided into three stages.

At the beginning of the evacuation, the occupants in the carriages depart for the exits but have yet reached it. Because the capacity of each exit is smaller than the total capacity of the allocated doorways, the number of waiting occupants increases linearly as the occupants has to wait at the exits. It is called stage **a**. When all of the occupants evacuate from the carriage, the number of waiting occupants reaches the peak at stage **b**. After reaching the peak, the number of the occupants decreases linearly according to the capacity of the exits at stage **c**. Since the number of the occupant is proportional to the exit capacity, the peak of the waiting occupant load at Exit 2 and Exit 3 is larger than that of the occupant load at Exit 3 and Exit 4. It can be seen from the simulated occupant evacuation that the time required to evacuate from the platform is 187 seconds, i.e., 3.13 minutes in this case.

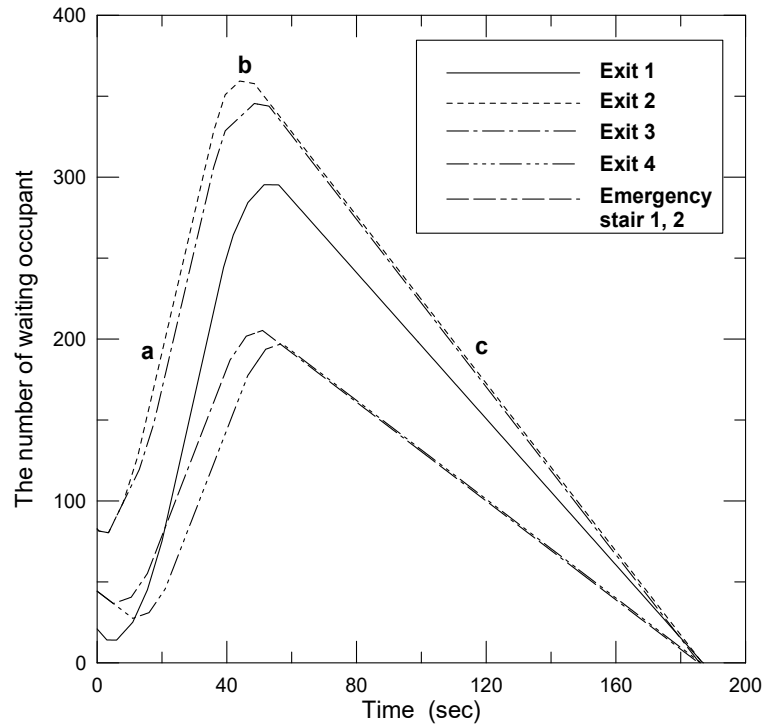


Fig. A-5 The dynamic changes in the number of waiting occupants in each platform exit for Case 1.

The total numbers of the occupants that have been evacuated from each platform and concourse exit are shown in Fig. A-6 and Fig. A-7, respectively. Figure A-7 shows that the time required for the passengers to evacuate in concourse level is 28 seconds which accounts for the time of the passengers from Exit 1 move to Exit A and the passengers move from Exit 4 to Exit B. Fifty seconds after the evacuation starts, the passengers in Exit 2 reach Exit A and the passengers in Exit 3 reach Exit B, which results in the linear increase in the number of occupants evacuated. Fig. A-7 shows the evacuating passengers in the concourse level at the final stage flow in from Exit 2 and Exit 3 only. In this case, the capacities of the Exit A and B are larger than those of the platform level exits. Therefore, there is no stagnation at the Exit A or B.

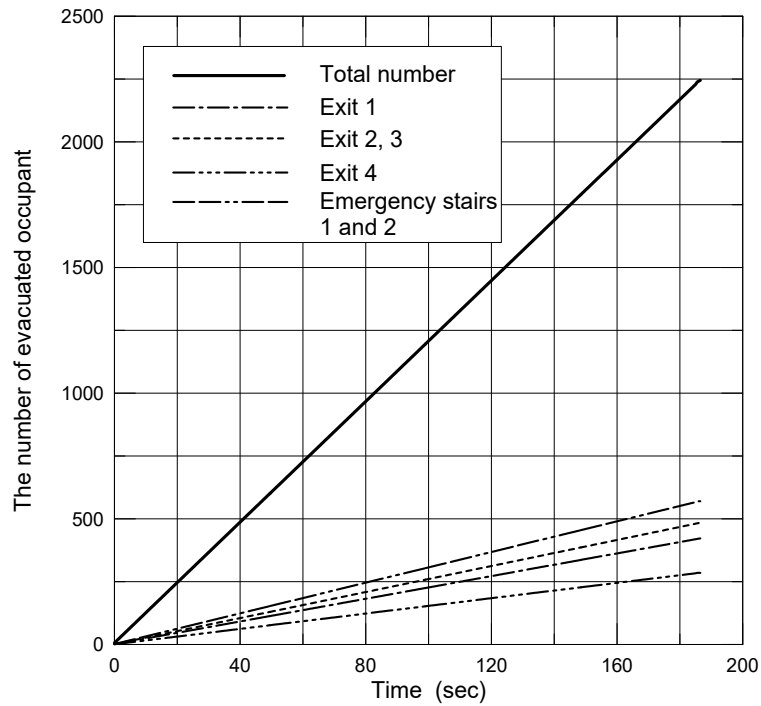


Fig. A-6 The total numbers of the evacuated occupants from each platform exit for Case 1.

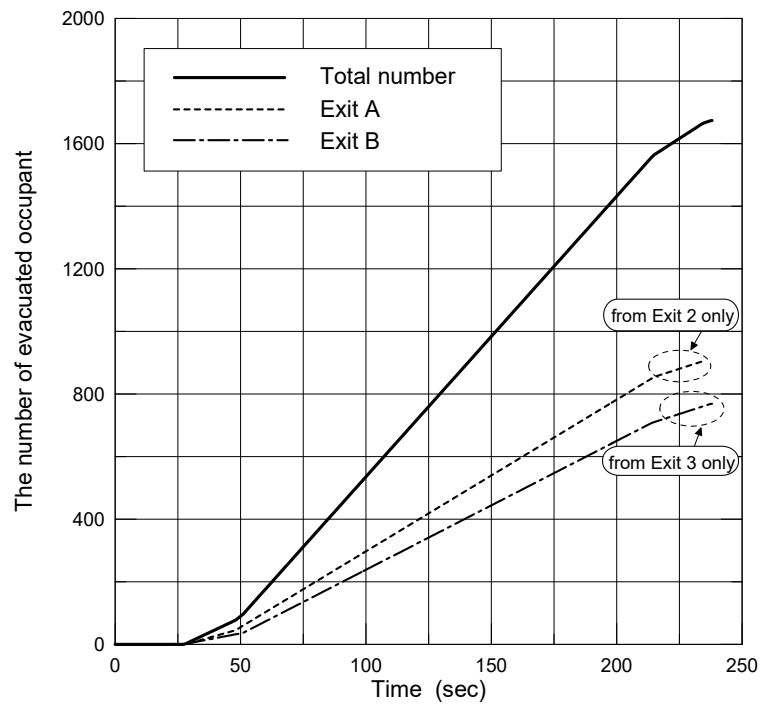


Fig. A-7 The total numbers of the evacuated occupants from each concourse exit for Case 1.

Figures A-8 and A-9 present the dynamic changes in the number of occupants that evacuate from each of the platform and concourse exits for Case 2. In this case, the

evacuation time from the platform is 224 seconds, i.e., 3.73 minutes. In figure A-9, it can be seen that the passengers from Exit 1 of platform level first arrive at Exit A and it approximately takes 28 seconds. In addition, Fig. A-9 **a** shows that a certain amount of passengers steadily move on this route continuously. Approximately 49 seconds after the evacuation, the passengers in Exit 2 arrive at Exit A. In Fig. A-9 **b**, however, stagnation occurs resulting from the smaller capacity of Exit A compared to the combined capacity of Exit 1 and Exit 2. When the evacuation from Exit 1 and Exit 2 completes, the number of waiting occupants decreases linearly with the capacity of Exit A, as seen in Fig. A-9 **c**. With regards to Exit B, there is no stagnation. In Case 2, the last passenger spends 276 seconds to reach and pass the fare barrier. The dynamic change in the number of evacuated occupants in each concourse exit for Case 2 is shown as in Fig. A-10.

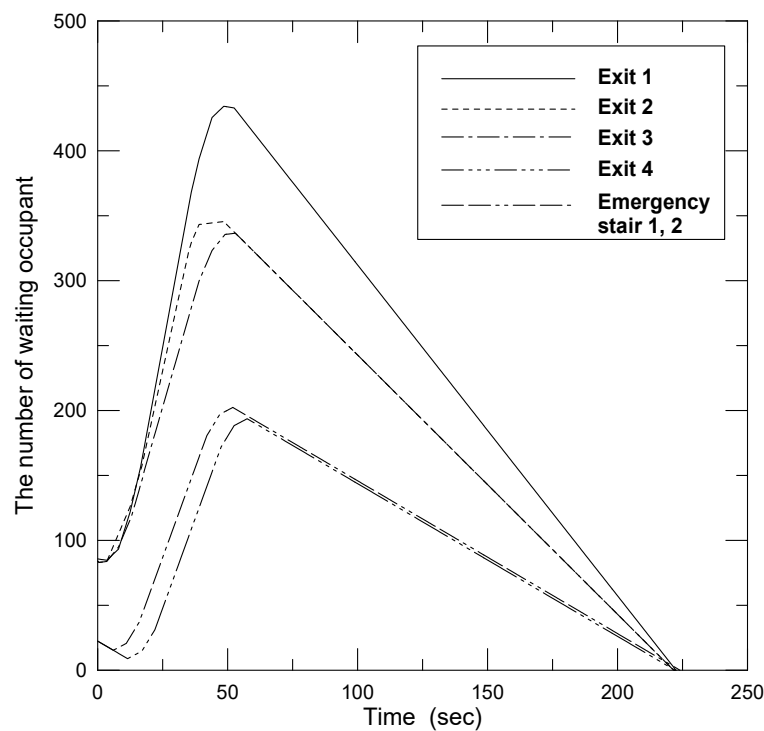


Fig. A-8 The dynamic changes in the number of waiting occupants in each platform exit for Case 2.

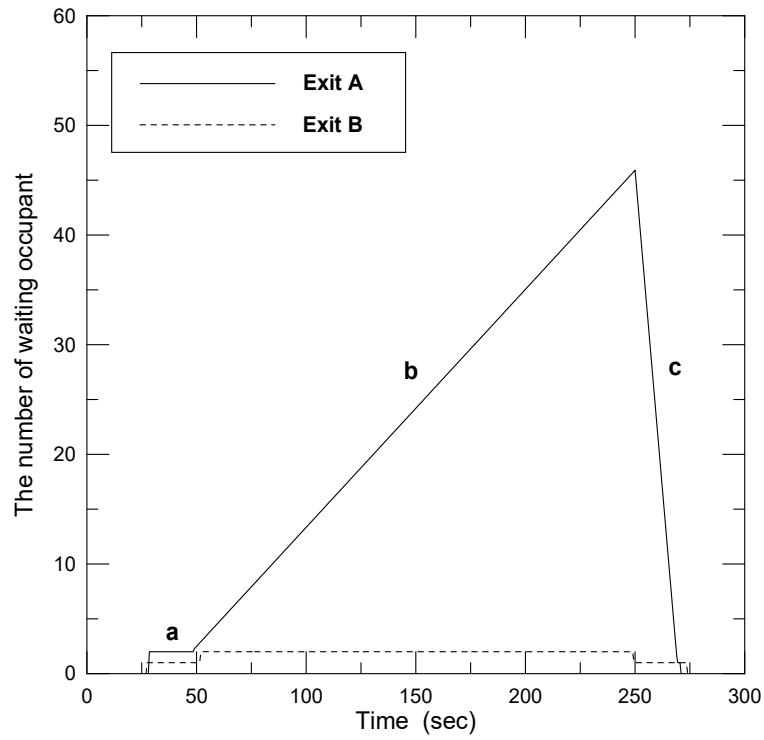


Fig. A-9 The dynamic changes in the number of waiting occupants in each concourse exit for Case 2.

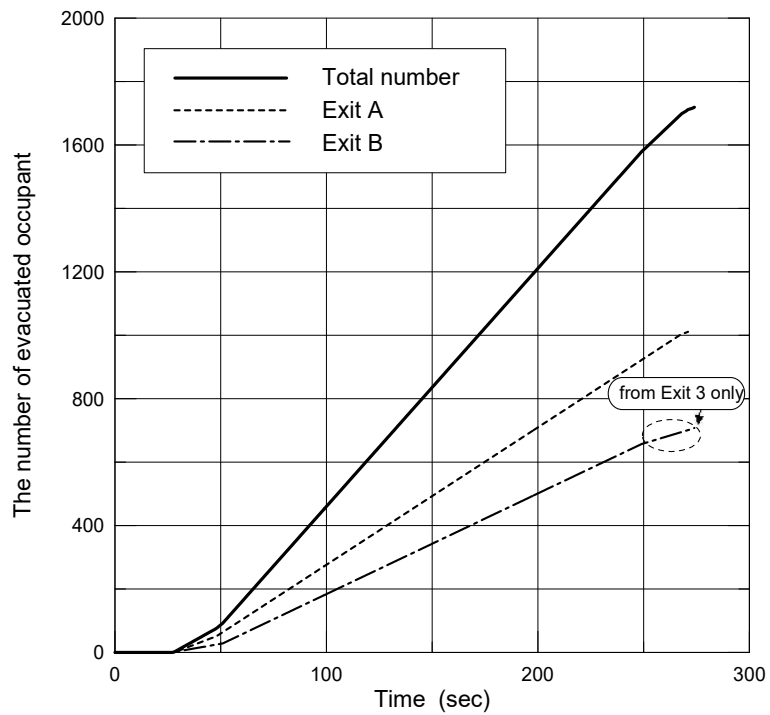


Fig. A-10 The dynamic changes in the number of evacuated occupants in each concourse exit for Case 2.

The dynamic changes in the numbers of waiting occupants for Case 3 are displayed in Fig. A-11. Case 1 and Case 3 are similar; larger occupant load in Case 3 leads to longer time required for completing the evacuation. The dynamic changes in the number of the occupants that wait and evacuate from each of the platform exits for Case 4 are presented in Fig. A-12. The results in the dynamic change in the total number of waiting and evacuated occupants from each of the concourse exits are presented in Figures A-13 and A-14. There are points of similarity between Case 4 and Case 2; larger occupant load in Case 4 leads to longer time required for the completion of the evacuation.

The results of the evacuation time for Case 1 to Case 4 are presented in Table A-7. SIMULEX [A2] and CFDOM [A3] are used for studying the evacuation time. It should be noted that the behavior of the occupants in this study is defined that only the movement aspect of the evacuation is simulated and the occupant is assigned a specific unimpeded velocity as well as the NFPA 130. However, the SIMULEX is a partial behavior model and the implicit behavior of the occupants is modeled. The implicit behavior represents those models that attempt to model behavior implicitly by assigning certain response delays or occupant characteristics that affect movement throughout the evacuation [A4]. The differences in these two models occur when the occupants become closer in a high density situation, resulting in queuing and congestion within the building for the SIMULEX.

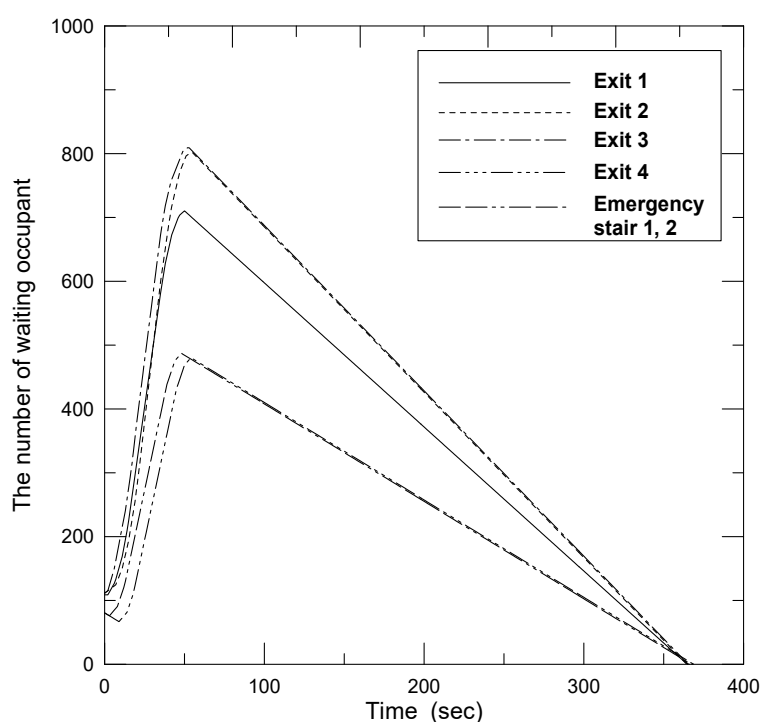


Fig. A-11 The dynamic changes in the numbers of waiting occupants from each platform exit for Case 3.

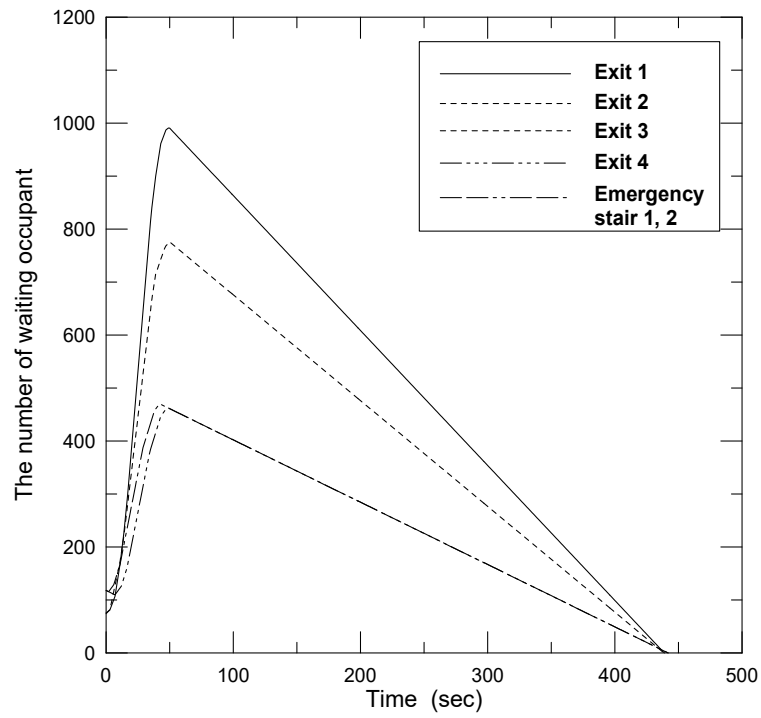


Fig. A-12 The dynamic changes in the numbers of waiting occupants from each platform exit for Case 4.

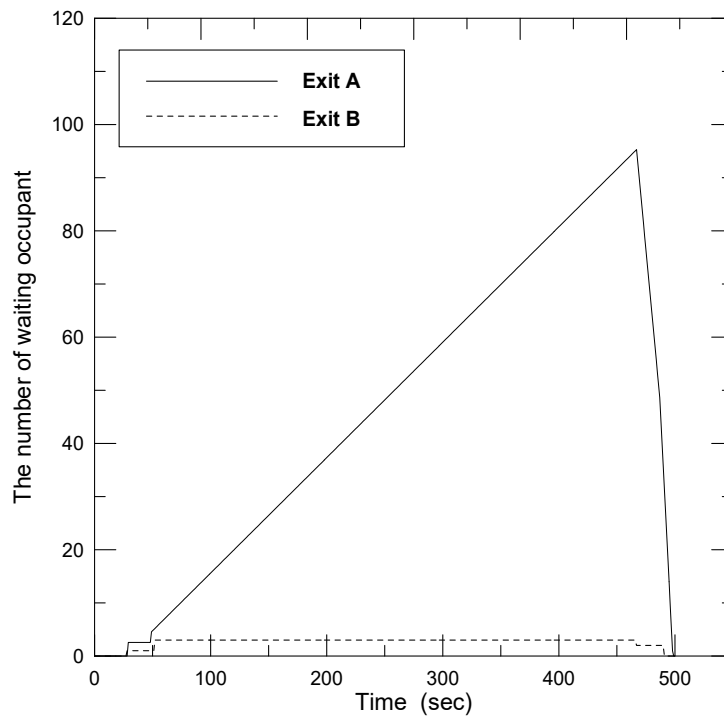


Fig. A-13 The dynamic changes in the number of waiting occupants in each concourse exit for Case 4.

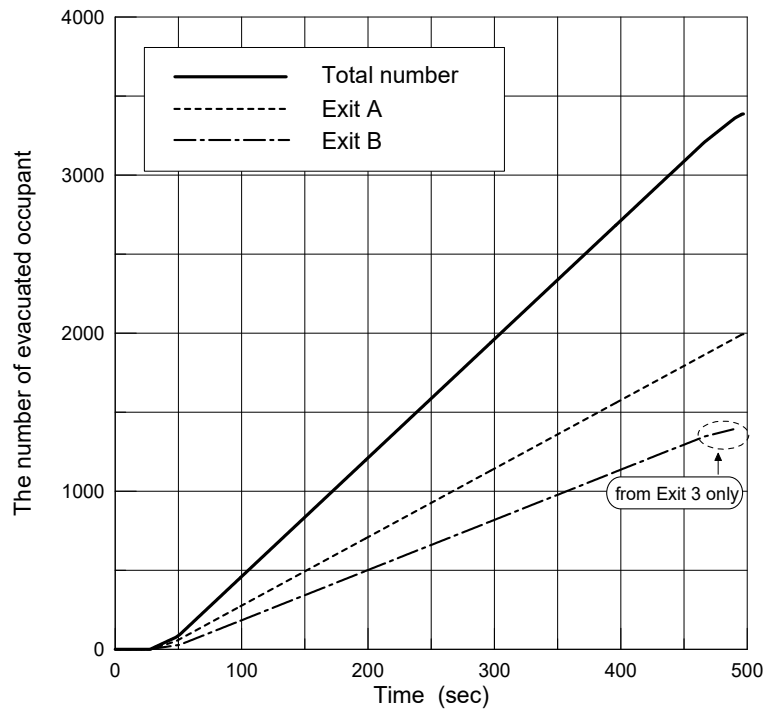


Fig. A-14 The dynamic changes in the number of evacuated occupants in each concourse exit for Case 4.

Tables A-7 The results of evacuation time with control volume method for different scenarios (min)

Location	Test No. 1 (≤4 mins)	Exit A	Exit B	Test No. 2 (≤6 mins)
Scenario 1				
Case 1	3.13	3.94	3.98	4.93
Case 2	3.73	4.53	4.60	5.55
NFPA 130 [A1]	3.11	-	-	4.93
SIMULEX [A2]	5.17	-	-	9.95
CFDOM[A3]	5.64	-	-	-
Scenario 2				
Case 3	6.15	6.97	7.01	7.95
Case 4	7.32	8.32	8.18	9.26
NFPA 130 [A1]	6.14	-	-	7.96
SIMULEX [A2]	10.37	-	-	16.67
CFDOM[A3]	10.14	-	-	-

The occupant type used for the SIMULEX is “office type” which specifies the walking speed and body size to be 40 % male, 30 % female, and 30 % average. For the SIMULEX, the user can create an alternate distance map for an individual, group, or several groups in which certain exits are blocked from the population using the distance map. In this study, the alternate distance map is used for all cases, which assumes the path and the exit chosen by passengers as in section A5.2. The pre-movement time is not also considered. Among the four cases, the results of the evacuation time for Case 1 and Case 2 can meet the criteria of NFPA 130 standard [A1] and Case 3 and Case 4 can not. As mentioned above, it is resulted from different occupant load. By using NFPA capacity, this study yields almost the same result as NFPA. Investigated capacity input in Case 3 and Case 4 yields longer evacuation time. It requires even more time adopting SIMULEX [A2] and CFDOM [A3] calculation. In the SIMULEX simulations, when the occupants became closer in a high density situation around the exits and that resulted the jamming and a conservative evacuation time. If the default distance map is used, the shortest path would be chosen by occupants and most of the occupants would jam at few exits and then the longer evacuation time would be required.

The two most important features in fire safety design of a fixed guideway transit or passenger rail vehicle are to provide sufficient time for evacuation in the event of a fire before the vehicle compartment becomes untenable and to prevent a self-propagating fire [A1]. Therefore, the design of the means of egress shall be also based on the emergency conditions and the human behaviors. For example, the exit selection behaviors do exist when many people escape a building with more than 1 exit, and people usually tend to follow others during walking and thus jammed at some exits. In the actual evacuation affairs, people are also observed to use the exits that they are familiar. A software or model that derives longer egress time should not be excluded but, on the contrary, should be paid more attention.

In control volume model, the measurement of the evacuation time starts as the passengers are at the carriages. It is different from NFPA which starts the measurement as the passengers are on the platform. It can be seen that the Test No.1 and Test No.2 results of NFPA and control volume model using NFPA parameters (Case 1 and Case 3) are very similar; especially in Scenario 1 which is the predefined occupant load of Taipei Metro Company. In this paper, using the investigated parameters generates longer evacuation time because the summation capacity of the escalators and staircases is smaller than NFPA 130 standard. This result justifies the rationality of the assumption, calculation and procedure of the control volume model.

A6. Conclusions of appendix

In this study, the dynamic characteristics of the evacuation course at each time-step for each of the exits have been derived by the control volume model. Although this model is more complicated in calculation, it is proven to be a reasonable mathematic model as it yields similar results using the same occupant loads and capacities as NFPA 130 standard. The calculation procedures of the control volume model uses both NFPA 130 and investigated parameters that enable us to identify the relationship among time, exit and the number of people stagnating and understand what happens during evacuation in underground MRT stations. The concept of the control volume model can provide some insights when designing evacuation software. In addition, it is clear that there are significant periods of 'waiting' in some of the evacuation sequences. There is a basic relationship between the area of the safe space, where waiting can happen, the receiving flow of people and the capacity of the exits from that space.

Individual behaviour has caused real-world evacuation to deviate from theory. It draws more attention as to how to apply reasonable calculation and assumption to understand the most likely evacuation scenario in the event of fire. Nowadays, co-construction of multiple underground transportation systems has become a trend in Taiwan station engineering. The underground stations become massive and complicated as they incorporate many commercial activities. It is well known that passengers' life safety depends on whether passengers can evacuate safely before untenable conditions occur. Generally, the time required to egress called RSET consists of detection time, response time and movement time. To achieve safe evacuation and to enhance the Available Safe Egress Time (ASET), understanding human safety factors such as smoke, heat, visible distance and temperature are also important. Equal weight should be given to the awareness of human behaviour and the application and development of evacuation models, which can provide new thoughts for future station design and operation.

References

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