Simulation Modelling Practice and Theory 96 (2019) 101937

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

The numerical analysis of mass evacuation in Taipei 101 with control volume model

Guan-Yuan Wu[a,*], Masayuki Mizuno[b]

[a] Department of Fire Science, Central Police University, 56 Shu-jen Road, Ta-kang, Kwei-san, Tao-yuan, 333 Taiwan
[b] Graduate School of Global Fire Science and Technology, Tokyo University of Science, Japan

ARTICLE INFO

Keywords:
Evacuation
High-rise building
Evacuation simulation
Control volume model

ABSTRACT

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 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 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 508 m 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) 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.

1. Introduction

With increasing awareness of the importance of occupant safety and the desire to avoid disorder, the issues of 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 the large full-scale evacuation, and the results have been published [1–8].

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.

Many researches show that the first evacuation phase influences the evacuation procedure: this is called pre-movement phase,

* Corresponding author.
E-mail address: una210@mail.cpu.edu.tw (G.-Y. Wu).

https://doi.org/10.1016/j.simpat.2019.101937
Received 20 September 2018; Received in revised form 28 May 2019; Accepted 29 May 2019
Available online 30 May 2019
1569-190X/

which starts when the fire is detected and the occupants are alerted to evacuate [9]. D'Orazio et al. [10] 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. The numerical characteristics and dynamical features of this pre-movement phase have been investigated for different buildings and circumstances, such as offices [11], stores [12], schools [13,14], and theatres [15] etc. However, Liu and Lo [13] indicated that these numerical data showed wide distribution, depending on the type of building and activities in which people were engaged. Recently, several studies have proposed the interactive methodologies for assisting evacuation in a real situations, and in particular, for pre-movement time reduction [16–18].

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 of the fire floor but also the entire building [19]. Several studies have been reported in the literature dealing with the observation of merging flows on stairs [20–24]. Hokugo et al. [20] studied the confluence of two traffic flows in staircase and suggested that the merge ratios between stairs and floors be dependent upon which stream first established itself. Takeichi et al. [21] extended the earlier study of Hokugo et al. [20] 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 Hokugo et al. [20], Takeichi et al. [21] suggested that the merging behaviors at floor-stair interfaces are strongly influenced by physical attributes related to the geometry of architecture and the density of the crowds on the stairs. Galea et al. [22] examined the representation of the merging process at the floor-stair interface within a comprehensive evacuation model. 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 [22]. Based on computer simulations, Ding et al. [23] investigated the merging behavior at the floor-stair interface of high-rise building. Recently, Yajima et al. [24] investigated the characteristics of the walking and merging behaviors of the occupants descending to the staircase on the basis of observational data of a real total evacuation drill in a high-rise building, and found that there was an approximate equal sharing of the merging process at the stair landing (i.e. proximately 50:50).

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 [25,26].

The macroscopic models consider the evacuees as an integer with same characteristics so that the evacuation performance depends on the crowd flow velocity, crowd density, and physical factors of architectures. Regression model [27,28], gas-kinetics model [29], queuing model [30], and Takahashi model [31], etc. are included in macroscopic category. 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 [32–34], lattice gas (LG) [35,36], integrated network approach [37], spatial-grid evacuation (SGEM) [38], multi-grid [39], hybrid space discretisation (HSD) [40], affordance-based finite stat automata (FSA) [41], and cellular automata models [42–44] 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 [45], EXITT [46], and building EXODUS [47,48]. Generally, social forces, lattice gas (LG), spatial-grid evacuation (SGEM), multi-grid, hybrid space discretisation (HSD), affordance-based finite stat automata (FSA), and cellular automata models are regarded as discrete models. They are discrete in space, time, and state variables.

Recently, Gasparotto et al. [49] 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. [50] 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 [51].

It is well known that a properly planned evacuation strategy 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 studies of the potential availability of phased evacuation and the safe use of elevators strategy in fire evacuations have been conducted [52–54]. Koo et al. [52] presented new evacuation strategies for a heterogeneous population in high-rise building environments and compared them with traditional simultaneous evacuation strategy. They found a vertically phased evacuation strategy that varies delay times by physical location was not useful for the simulated building. Ronchi and Nilsson [53] 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. [54]. 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 [54].

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. [42] 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. Using the building EXODUS, the performance of elevator evacuation in Taipei 101 was studied by Hsiung et al. [55], and Chien and Wen [56]. They pointed out that elevator evacuation by the Taipei 101 can greatly shorten the evacuation time. Appling the AnyLogic package, Liao et al. [57] 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. [58]. 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.

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. Proulx [59] reviewed data sets on stairway movement where a complex set of behaviors, such as resting, investigation, and communication were involved. Some researchers reviewed and summarized the typical engineering variables used to describe stairwell movement during building evacuations. Peacock et al. [60] found that the mean movement speed of the 10-, 18-, 24-, and 31-story building evacuations were 0.48 m/s ± 0.16 m/s, with individual local movement speeds ranged from 0.056 m/s to 1.7 m/s. Fahy [61] 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. The NIST study [62] combined the collection of new staircase movement data for elderly and mixed-ability occupants, and office populations, with a review of egress movement on staircases.

Recently, Ma et al. [63] 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 470 m 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. Wu et al. [64] investigated human movement characteristics in the stairwell of super high-rise buildings in Taipei 101 and New Taipei City Hall, which are about 508 m and 140 m 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 [64].

For the evacuation safety of high-rise buildings in Japan [65] and Taiwan [66], the total egress time of the performance approach can be obtained by three parts 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 are considered as a homogeneous fluid. Meanwhile, the consequence of the performance approach for the evacuation of a super high-rise building leads to a fixed value of time only.

The aim of this study is to investigate the numerical analysis of mass evacuation in a super high-rise building with control volume model. This model has been applied to the evacuation time calculation in a high-rise building and the mass rapid transit (MRT) station by Wu et al. [67,68], and shown that the results of this model were quite reasonable. One of these basic assumptions of this model was to adopt 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 [67] using the control volume model, the simulation had been carried out to obtain the total building evacuation in a 9-story office building built by NFPA with a population of 300 persons/floor.

In this research, Taipei 101, a super high-rise building is the chosen object of evacuation simulation. Not only the occupant's distributions are not uniform, but also there are 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.

In this study, we focus on the total building evacuation and phased evacuation by the stairwells only. Occupants on each floor start to evacuate simultaneously, move to the exits, and use fire/smoke proof stairs to move downward to the ground floor. Based on the control volume model and the scenario analysis of emergency evacuation, we have presented an analytical approach to explore the process of mass evacuation rather than simulation. By varying the parametric inputs of merge flow ratio, coefficient of flow rate, and walking speed, the numerical results of mass evacuation in Taipei 101 are presented and discussed.

2. The descriptions of Taipei 101 and control volume model

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 once the world's tallest building, rising 508 m, is located at the east district of downtown Taipei City and the schematic view of the building is as shown in Fig. 1. 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 purpose. 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, temporary shelter floors of the tower, are designated as elevator transfer floor and sky lobby [56].

There are two pressurized stairwells which provide major escape routes for the occupants. When evacuation takes place for emergency events such as fires, all evacuees should choose one of these two evacuation stairwells where evacuees can move the building directly to ground floor, as shown in Fig. 2.

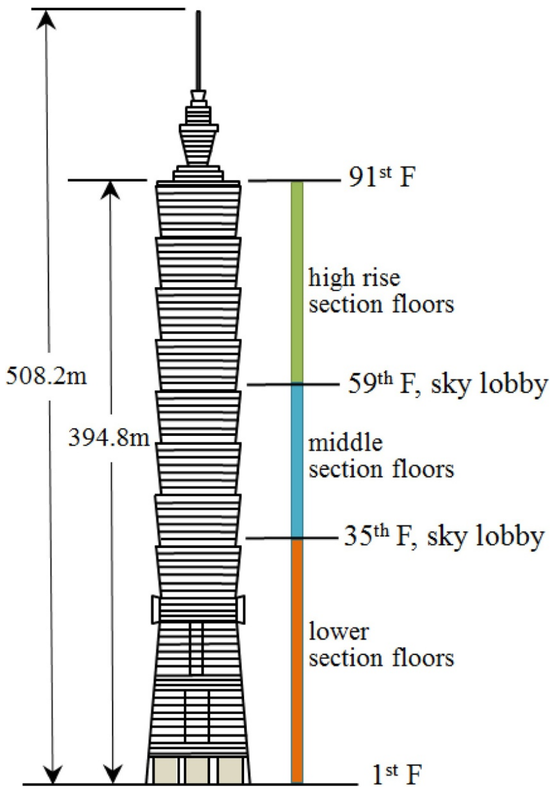

Fig. 1. The schematic view of Taipei 101.

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 1.4 m width and total 21 steps with the riser height of 20.0 cm and the tread of 24.0 cm as shown in Fig. 3. 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 study, the distance of a participant through a stair landing is simplified to walk along the middle line of the landing (see Fig. 3) as calculated in Refs. [61,64–66,69,70].

The length $\triangle l$ (m) of the adjacent floor can be obtained from the equation and shown as follows [69,70].

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

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.

Based on the prescriptive occupant load factors in Taiwan [66], the total number of occupants inside the building is estimated. Since Taipei 101 is of multiple functions, its peak usage time would be during the office days. For example, the number of office occupants is based on the density of 0.125 person/m^2 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 1.

2.3. Control volume model

2.3.1. Basic assumptions

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 as shown in Fig. 4. The closed surface is changed with time and the summation of

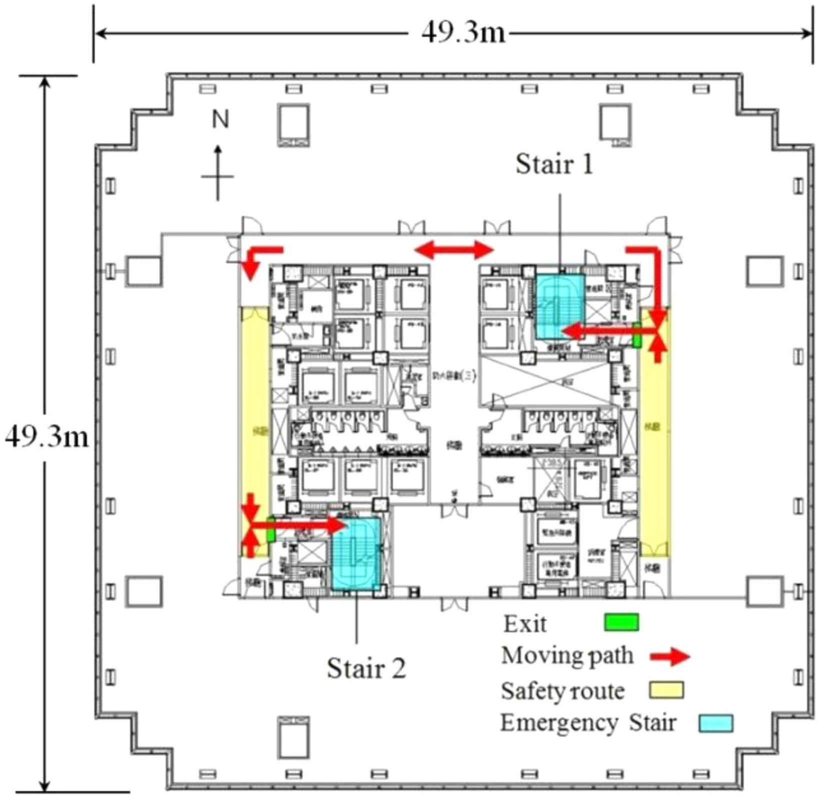

Fig. 2. The typical floor layout of evacuation strategy.

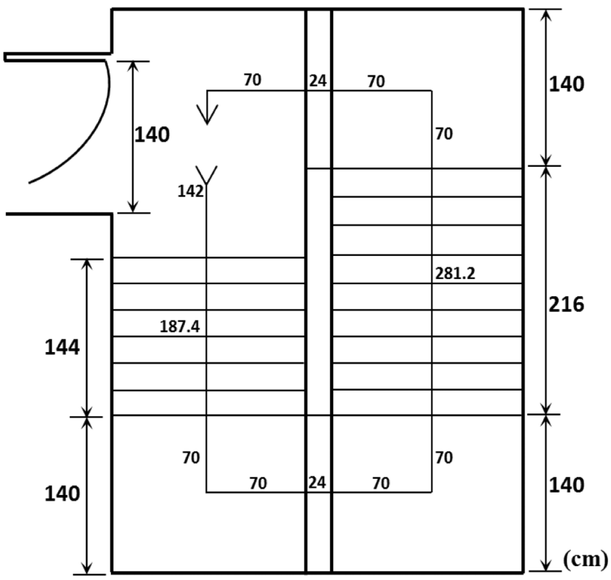

Fig. 3. Dimension of building stairs, Taipei 101 stair section on the 7th–91st floor.

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. On each floor, the merge flow ratio of the descending stair entry flow and exit flow is also a constant. In addition, the factors of 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

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

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

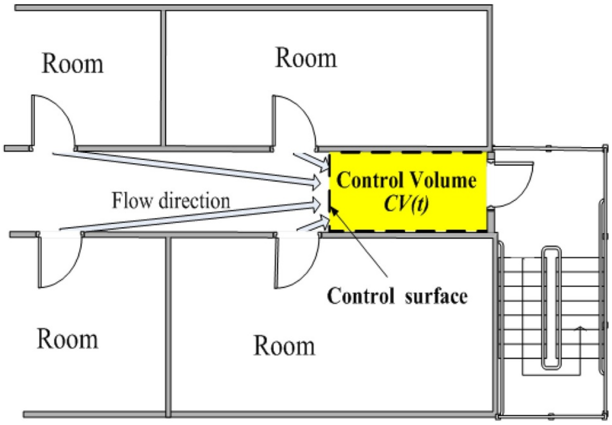

Fig. 4. The control volume model of floor evacuation.

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 the occupant number within the control volume.

The total number of occupants flowing to the control volume at certain time point t can be presented as follows [67,68]:

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

where $\dot{Q}_n(t)$ is the flow rate of the occupants at the n^{th} exit (door) moving to the control volume (persons/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 (persons/s). Because the number of occupants per unit area is 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). It should be noted that the effective width of the corridor is not equal to its actual width as occupants tend to flock around the exits.

2.3.2. Occupant movement

In this study, the occupants' movements during 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 $n+1$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 [67]. In the following contents, detailed calculations based on these occupant movement characteristics will be provided.

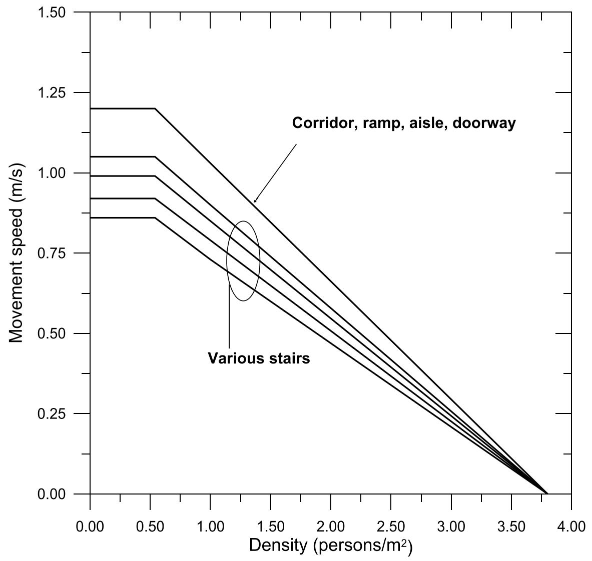

Fig. 5. The fundamental diagram of occupant movement [61].

3. Modeling and analysis

3.1. Movement parameters

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

In this study, we divide each floor in half to produce two exit calculation zones and refer to NFPA in the algorithm of evacuation time calculation [61]. 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 37 m 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/m^2. With the same algorithm, the density between the ground and 6th floor is 0.27 persons/m^2.

The fundamental diagram of occupant movement for the relationships between densities, velocities, and flows is cited from NFPA (see Ref. [61]) as shown in Fig. 5. If the population density is less than 0.05 persons/ft^2 (0.54 persons/m^2) 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/ft^2 (3.8 persons/m^2), no movement will take place until enough of the crowd has passed from the crowded area to reduce the density [61]. Between the density limits of 0.54 and 3.8 persons/m^2, the relationship between speed and density can be considered as a linear function and shown as [61]

$$S = k - akD \tag{3}$$

where S is speed (m/s) along the line of travel, D is density (persons/m^2), $a = 0.266$ and $k = 1.4$ when calculating speed in meter per second and density in persons per square meter [61]. 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.

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/m^2, 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 [61], 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/m for the different interval floors, respectively.

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 [61]. 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 1.4 m 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.

Table 2
The parameters in the Taipei 101.

Exit route element	Parameter
Floor to floor height (7th–91st F)	4.2 m
Floor to floor height (ground–6th F)	6.3 m
The walking speed (7th–91st F)	0.97 m/s
The walking speed (ground–6th 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, $F_{s(\text{corridor})}$	
7th–91st F	1.12 (persons/s/m)
Ground–6th F	0.32(persons/s/m)
The exit specific flow, $F_{s(\text{exit})}$	
7th–91st F	1.30 (persons/s/m)
Ground–6th F	0.49 (persons/s/m)
The exit flow, $F_{s(\text{exit})}$	
7th–91st F	1.43 (persons/s)
Ground–6th F	0.54 (persons/s)
The stair specific flow, $F_{s(\text{stair})}$	
7th–91st F	0.94 (persons/s/m)
Ground–6th F	0.47 (persons/s/m)
The stair flow $F_{c(\text{stair})}$	
7th–91st F	1.09 person/s (65 persons/min)
Ground–6th F	0.54 person/s (32 persons/min)
The maximum capacity of the stair	17 persons
The maximum capacity of the landing	24 persons

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 m − (0.15 m + 0.09 m) = 1.16 m. Between the 7th and 91st floor, the specific flow for the stairway $F_{s(\text{stair})}$ is 1.30 (persons/s/m) × 1.1 m (door) /1.16 m (stair) = 1.23 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 [61]. 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 2.

3.2. Evacuation modeling

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

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 m/s and 1.2 m/s, respectively. Therefore, the evacuation time of stage 1 is 38 s for the floor interval between the 7th and 91st floor, and 31 s for the floor interval between the ground and 6th floor.

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 [61],

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

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

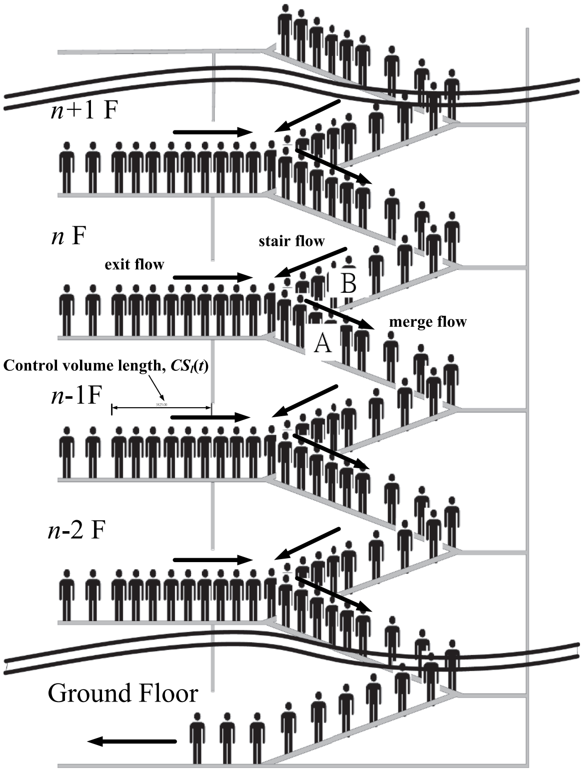

Fig. 6. Stage 3: merge stage [67].

Therefore, the densities of the stairway flow D can be obtained and shown as approximately 1.88 and 065 persons/m^2, 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 s. 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 s.

After 22.98 s, 1.09 × 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.

3.2.3. Stage 3: the occupants of the n + 1th floor merging with the crowd originally occupying the nth floor

As mentioned in Ref. [67], when the stair entry flow arrives at the lower floor and meets with the sources of exiting occupants as shown in Fig. 6, 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:

$$R = \dot{Q}_{n,s}/\dot{Q}_{n,e} \tag{5}$$

where $\dot{Q}_{n,s}$ (persons/s) is stair flow of the $n + 1$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. 6) reaches the maximum stair capacity, the stagnation occurs (as mark B in Fig. 6) 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.

$$\dot{Q}_{n,e} = \frac{\dot{Q}_{s(\max)}}{1 + R} \tag{6}$$

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

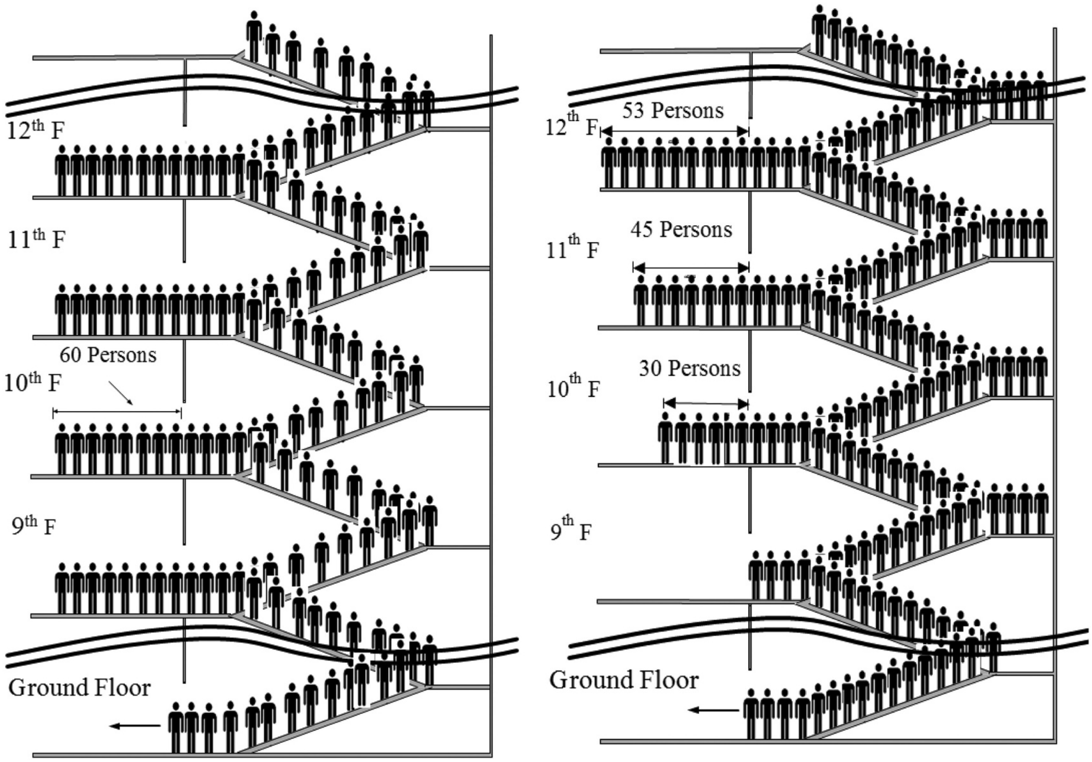

Fig. 7. The number of the waiting occupants at stage 3 (a) and the stagnating occupants reached the maximum (b).

described as follows [67].

$$\dot{Q}_{n,s} = \dot{Q}_{s(\max)} \times \left(\frac{R}{1+R}\right)^{n-1} \tag{7}$$

$$\dot{Q}_{n,e} = \dot{Q}_{n,s} \times \frac{1}{R} \tag{8}$$

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. 7(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. 7(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.

3.2.5. Stage 5: the completion of the evacuation

Eqs. (7) and (8) 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 [67].

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. [24]. The results showed that the merging ratio at staircase landing is nearly 1.0.

Table 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	$F_{s(\text{exit})}$ = 1.30 (7th-91st F)	The parameter values of walking speeds and specific flow are the same as NFPA [61]
Case 2	R = 0.5 (33:66)	v_s = 0.50 (7th-91st F)	$F_{s(\text{exit})}$ = 1.30 (G-6th F)	
Case 3	R = 1.5 (60:40)	v_s = 0.83 (G-6th F)	$F_{s(\text{stair})}$ = 0.94 (7th-91st F)	
Case 4	R = 2.0 (66:33)		$F_{s(\text{stair})}$ = 0.47 (G-6th F)	
Case 5	R = 1.0 (50:50)			Phased evacuation, the fire on the 22nd 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 [65].
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 valuesof walking speeds and specific flows are the same as Wu et al. [64, 68].

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 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 corresponding values of merge ratio 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 [61] 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 [65] are assigned to case 6, and those of Wu et al. [64, 68] 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 [65] 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 drills of Taipei 101 within the 80th −1st floor i.e. 344 m in height [64]. The parameter value of specific stair flow is the same as in Ref. [68], 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.

As mentioned previously, total building evacuation is assumed that all building occupants are expected to evacuate simultaneously by using 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 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 lack of reliable data in relation to the times associated with particular behaviors [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 [67]. 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. 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 phase 2 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 relatively safe place.

Table 4
The priority of stairway evacuation.

Floor	Countermeasures	Priority of stairway evacuation
The 3rd 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 2nd 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

Table 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 [61].
NFPA [61]	94.4	This result is obtained by A-first order approximation.
Melinek and Booth [71]	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 [61].
Building EXODUS [56]	94.78	Designated exits are assigned.
	120.88	No person's evacuation behavior mode is designated.
Japan [65]	89.57	Verification method of evacuation safety, Route B

4. Numerical results and discussions

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 2–91 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 evacuation calculation of control volume method, the occupants of the 2nd floor are the first ones to complete evacuation (91 s) and the occupants of the 91st floor are the last ones. The total evacuation time for 12,200 persons is estimated at 96.67 min (5800.3 s). In order to compare the numerical results of this study with different evacuation literature/codes, the total evacuation times of Taipei 101 with different methods are shown in Table 5.

4.1.1. The first-order approximation (NFPA) [61]

As illustrated previously, if all occupants in the building start evacuation at same time, each stairway can discharge 65.0 persons/min. By the mean of the first-order approximation (NFPA) [61], the persons above the first floor require approximately 93.85 min to pass the exit, and an additional 0.57 min (34.5 s.) travel time is required for the movement from the second floor from the exit. The total minimum evacuation time is estimated at 94.4 min (5664 s).

4.1.2. The method of Melinek and Booth [71]

According to the evacuation situations, the egress time [71] 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

$$t_1 = \frac{nN}{F_s W} + t_s \tag{9}$$

$$t_n = \frac{N}{F_s W} + nt_s \tag{10}$$

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 s (96.2 min).

4.1.3. Building EXODUS evacuation software [56]

Chien and Wen [56] applied the Building EXODUS evacuation software to analyze the time needed for building evacuation of Taipei 101. A set of software default values are used, namely no person's evacuation behavior mode is designated. The time required for the last person exiting from the first floor of the building to the exit is set at 2 h and 52.5 s (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 h and 34 min (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 [61], the method of Melinek and Booth [71], and EXODUS evacuation software [56] (designated exits are signed). Therefore, the analytical method in this study is reasonable.

4.1.4. Japan‘s verification method of evacuation safety [65]

In Japan, Building Standard Law (BSL) is applicable to all buildings built, and it consist of provisions both for fire resistance and evacuation safety. For evacuation safety of buildings, Route B is a performance approach which is associated with the means of the verification method of evacuation safety [65]. In this approach, the total egress time can be obtained by three parts 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 min, respectively. Moreover, an additional 54.52 min queuing time is required to pass the exit. The total egress time is expected to be 89.57 min.

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

4.2. Effect of different merge flow ratios

Simulation results for cases 1 to 4 with evacuation time versus floor number for different merge ratios are presented in Tables 6 and 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 s 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 s. This is because no occupant had been assigned beneath this floor (i.e. 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 s 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 a smaller merge ratio has a smaller impact on the 19th floor's exit flow. Moreover, there are two mechanical floors beneath the 19th floor, and that provides the free movements

Table 7
The numerical results for different merge flow ratios.

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

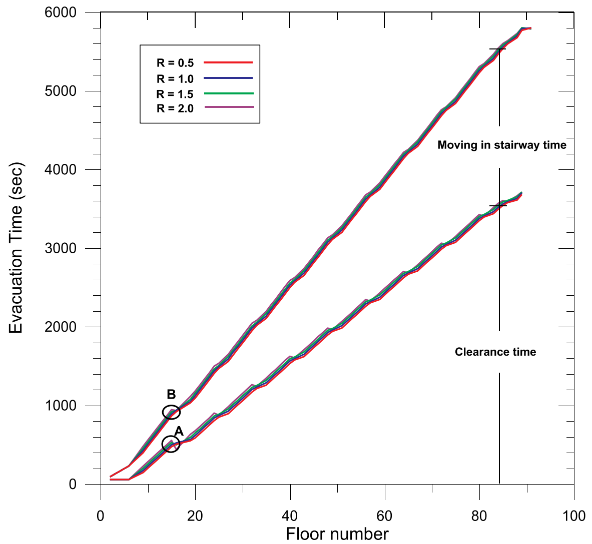

Fig. 8. The numerical results of the evacuation process for different merge ratios.

for the occupants from the 19th floor at the initial evacuation process.

Table 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 s. It is well known that the higher floor takes the longer evacuation time. Nevertheless, 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.

Fig. 8 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 having reached the ground and entered to stairwell from the floors 2 to 91, respectively. For each floor, the difference between the lower line and floor axis is the clearance time; the difference between the lower line and upper line is the time for the last occupant of each floor moving in the stairway. It can be clearly seen from Fig. 8 that except for 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.

In order to figure out the phenomena of points A and B, Fig. 9 and Table 8 show the times of the occupants on the floors 9 to 16 entered in the stair; Fig. 10 and Table 9 show the results of the occupants evacuated the building. From the Fig. 9 and Table 8, it is easy to find that the occupants on the 16th floor enter the staircase earlier than those of the 15th floor with R = 1.5 and 2.0. Analyzing the causes of these results, the main cause is that the 17th and 18th floors are mechanical floors, there will be no exit flow

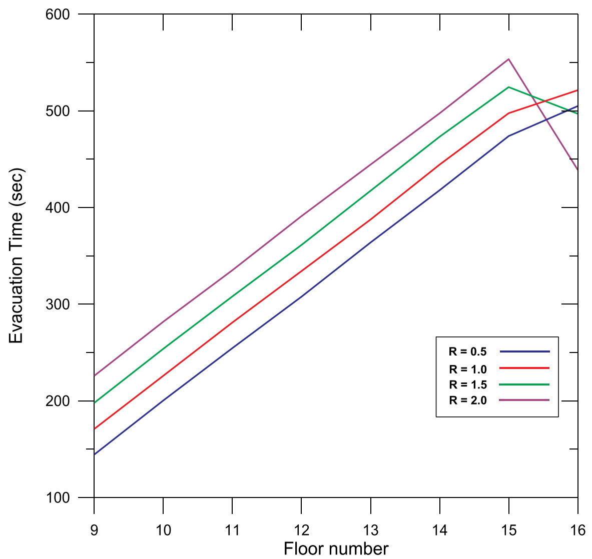

Fig. 9. Comparison of the evacuation times with different merge ratios.

Table 8
The numerical results for different merge flow ratios on floors 9–16.

Evacuation	Merge flow ratio $R = 0.5$	$R = 1.0$	$R = 1.5$	$R = 2.0$
All persons on the 16th F have evacuated	505.1	521.5	497.1	438.8
All persons on the 15th F have evacuated	473.9	497.6	524.6	553.5
All persons on the 14th F have evacuated	417.9	444.4	473.2	497.6
All persons on the 13th F have evacuated	363.8	387.5	417.3	444.4
All persons on the 12th F have evacuated	307.8	334.3	361.3	391.1
All persons on the 11th F have evacuated	254.6	281.1	308.1	335.2
All persons on the 10th F have evacuated	200.5	226.1	254.0	282.0
All persons on the 9th F have evacuated	144.5	171.0	198.0	226.0

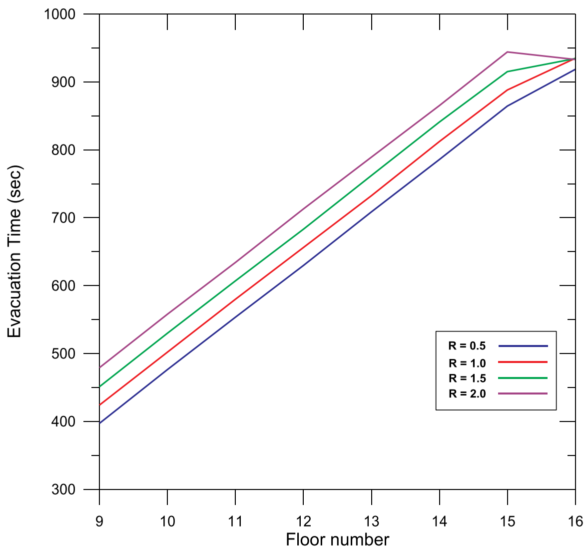

Fig. 10. Comparison of the evacuation times with different merge ratios.

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 mechanical floors and higher values of merging ratio. The similar interesting phenomenon is repeated in every 8 floors.

From Tables 8 and 9, it can be seen 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 s and 553.5 s, respectively; the occupants on the 16th floor and the 15th floor have evacuated the building at 933.1 s and 944.1 s, respectively. It is interesting to note that though the difference of the clearance time is 115 s 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 significant effect on the evacuation process in which the occupants are engaged in the stairwell.

Table 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 $R = 0.5$	$R = 1.0$	$R = 1.5$	$R = 2.0$
16th F	918.6	935.0	934.5	933.1
15th F	864.5	888.2	915.2	944.1
14th F	785.6	812.1	840.9	865.2
13th F	708.5	732.3	762.0	789.1
12th F	629.6	656.1	683.1	712.9
11th F	553.5	580.0	607.0	634.1
10th F	476.4	502.0	530.0	557.9
9th F	397.0	424.0	451.0	479.0

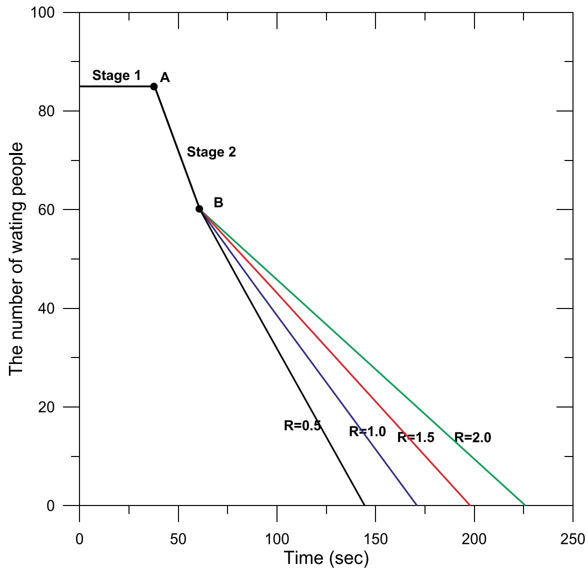

Fig. 11. The evacuation process of the occupants for different merge ratios on the 9th floor.

Fig. 11 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 at the 65 persons/min. At the 38th second (as point A in Fig. 11), occupant flow starts through the exit. $F_{c(\mathrm{stair})}$ through the exit is 65 persons/min for the next 23 s. At the 61st second (as point B in Fig. 11), 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. 11, it can be easily found that the higher value of merge ratio is, the longer time it takes the occupants of the 9th floor to evacuate.

The number of waiting people versus time features for different merge ratios on the 41st floor and 75th floor are shown in Figs. 12 and 13, 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. 12 shows that the higher value of merge ratio results in less waiting occupants at 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 a mechanical floor, and time of merging for the 41st floor's exit flow and the 43rd floor's stair flow is postponed (about 46 s). Furthermore, when the stair flow from 41st floor

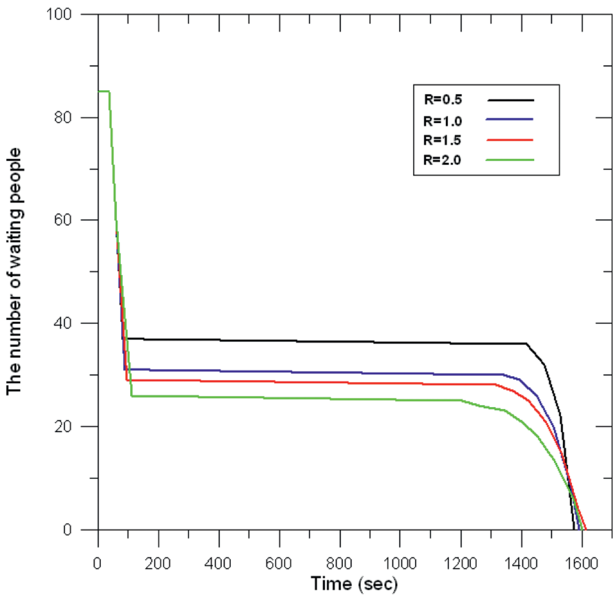

Fig. 12. The evacuation process of the occupants for different merge ratios on the 41st floor.

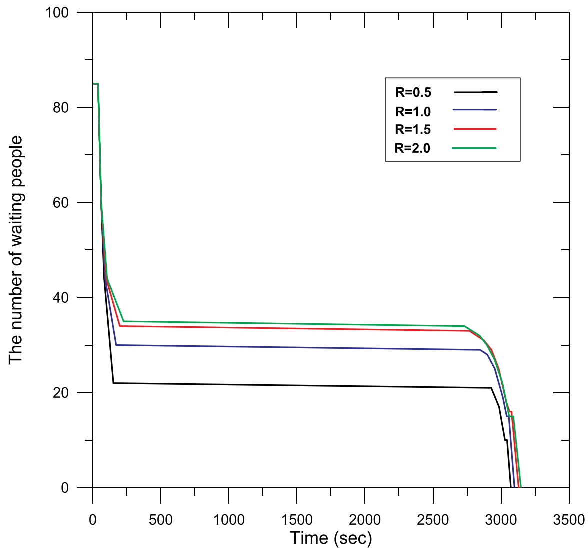

Fig. 13. The evacuation process of the occupants for different merge ratios on the 75th floor.

merges with 40th floor's exit flow, the stair flow from the 41st floor is 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 is the lowest value (26 persons) on the 41st floor at the beginning of stage 4.

Conversely, Fig. 13 shows that the higher value of merge ratio results in 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 a mechanical floor, there is no exit flow from the 74th floor, and the exit flow of the 75th floor takes the lead in entering the stairwell for the lower value of merge ratio. Therefore, the lower value of merge ratio causes the smaller number of waiting occupants on the 75th floor. As noted previously, after the time of merging the higher values of merging ratio takes the lead in entering the stairwell. This opposite feature at the stage 4 presented in Figs. 12 and 13, 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 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. 14. Overall, the evacuation time is proportional to the floor number, the higher floor takes longer time to enter the staircase. From Fig. 14, except the floors 9 and 19, the numbers of waiting people at 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.

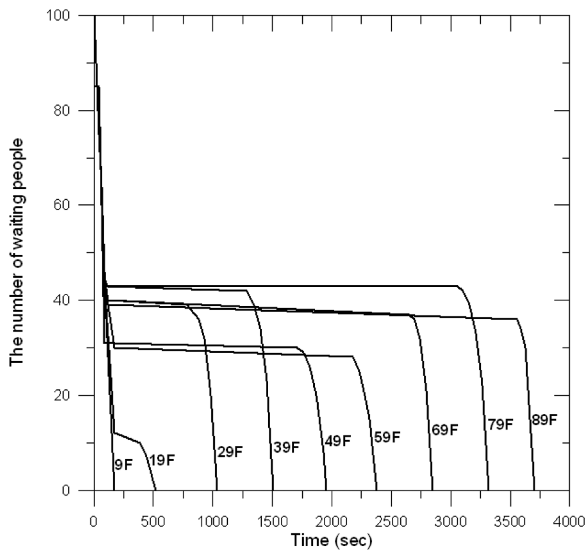

Fig. 14. The evacuation process of the occupants for different floors with $R = 1.0$.

Table 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

4.3. 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 phase 1 to evacuate, the occupants on the floors 25 to 91 are the evacuees of phase 2, and the occupants on the floors 2 to 20 are the evacuees of 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 is no merging before arriving at the ground floor. The second scenario is assumed that phase 3 begins when the last one of the occupant flow of phase 2 passes through the 21st floor. The results of the phase evacuation for different scenarios are presented in Table 10.

In this case, the travel distance between the ground floor and the 21st F is 264.2 m and the time required for the occupant flow to the ground floor is 528.5 s. 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 at 878.9 s. For scenario 2, the activating time of phase 3 is much earlier than that of the scenario 1. In fact, there are 576 persons remaining in the stairwell associated with phase 2 at the beginning of phase 3. Therefore, the total number of occupants at the beginning of phase 3 becomes 1526 (576 + 950). Since the calculated stair flow is 1.09 persons/s in this study, the required time to evacuate is 1400 s. For scenario 1 and 2, the total evacuation time is 6331.3 and 6170.0 s, 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.

4.4. Effect of different walking speeds and specific flows

Tables 11 and 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 11 and 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 [65], the calculated stair

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

Evacuation	Case 1	Case 6	Case 7
All persons on the 91st F have evacuated	93.0	70.0	97.9
All persons on the 89th F have evacuated	3701.3	2094.6	4133.6
All persons on the 83rd F have evacuated	3462.7	1963.6	3858.0
All persons on the 81st F have evacuated	3405.9	1930.3	3796.5
All persons on the 75th F have evacuated	3099.4	1759.5	3452.0
All persons on the 73rd F have evacuated	3042.6	1726.2	3394.3
All persons on the 67th F have evacuated	2738.0	1555.4	3049.8
All persons on the 65th F have evacuated	2681.1	1523.2	2988.3
All persons on the 59th F have evacuated	2374.7	1351.3	2643.8
All persons on the 57th F have evacuated	2317.8	1319.1	2586.1
All persons on the 51st F have evacuated	2013.2	1148.3	2241.6
All persons on the 49th F have evacuated	1956.3	1115.1	2180.1
All persons on the 43rd F have evacuated	1649.9	944.2	1835.6
All persons on the 41st F have evacuated	1593.0	910.9	1777.9
All persons on the 35th F have evacuated	1286.6	740.1	1431.5
All persons on the 33rd F have evacuated	1231.6	707.9	1371.9
All persons on the 27th F have evacuated	925.1	536.1	1029.3
All persons on the 25th F have evacuated	870.1	503.8	966.0
All persons on the 19th F have evacuated	565.5	335.2	628.9
All persons on the 16th F have evacuated	521.5	312.6	564.7
All persons on the 9th F have evacuated	171.0	115.0	182.0
All persons on the 2nd–6th F have evacuated	55.2	48.7	60.6

Table 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
91st F	5800.2	3425.7	5836.8
89th F	5789.1	3416.0	5825.7
83rd F	5413.0	3198.0	5438.3
81st F	5310.2	3135.7	5339.6
75th F	4866.2	2877.9	4883.4
73rd F	4763.5	2815.6	4788.4
67th F	4321.3	2557.8	4332.2
65th F	4218.5	2496.6	4233.5
59th F	3774.5	2237.7	3777.3
57th F	3671.7	2176.5	3682.3
51st F	3229.5	1918.7	3226.1
49th F	3126.8	1856.4	3127.4
43rd F	2682.7	1598.6	2671.2
41st F	2580.0	1536.3	2576.2
35th F	2135.9	1278.5	2118.1
33rd F	2035.0	1217.3	2021.3
27th F	1591.0	958.5	1566.9
25th F	1490.1	897.2	1466.4
19thF	1047.9	641.6	1017.6
16th F	935.0	575.5	897.5
9th F	424.0	276.4	384.5
2nd 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)

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 [65], 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 some time, but the purely queuing time of Japan's method (54.52 min) is quite consistent with the result of this study (57.09 min).

Fig. 15 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

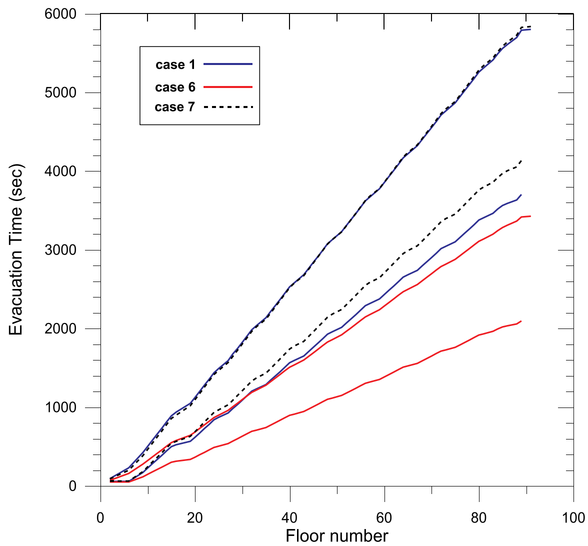

Fig. 15. Comparison of the evacuation times with different cases.

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 min) 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.

5. Conclusions

In this study, 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 [61], the method of Melinek and Booth [71], and EXODUS evacuation software [56] (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 cases 1 to 4, in spite of the fact that 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 s 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 more 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 to reach 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 applied to work out low-risk designs for the width of exits or corridors, and the sizes of area where 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 to the evacuation process of super high-rise building.

The merging behavior, pre-movement, the factors of fatigue, and counter flow are not considered in this study. It should be noted that these results of mass evacuation cannot represent the general features for disabled people, older people, and children. According to Low [72] 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 [72]. To fully understand overall emergency evacuation times for super high-rise building evacuation, 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.

References

[1] E.R. Galea, J. Shields, D. Canter, K. Boyce, R. Day, L. Hulse, A. Siddiqui, L. Summerfield, M. Marselle, P. Greenall, Methodologies employed in the collection, retrieval and storage of human factors information derived from first hand accounts of survivors of the WTC disaster of 11 September 2001, J. Appl. Fire Sci. 15 (4) (2008) 253–276.
[2] E.D. Kuligowski, D.S. Mileti, Modeling pre-evacuation delay by occupants in World Trade Center Towers 1 and 2 on September 11, 2001, Fire Saf. J. 44 (4) (2009) 487–496.
[3] T.J. Shields, K.E. Boyce, N. McConnell, The behaviour and evacuation experiences of WTC 9/11 evacuees with self-designated mobility impairments, Fire Saf. J. 44 (6) (2009) 881–893.
[4] N.C. McConnell, K.E. Boyce, J. Shields, E.R. Galea, R.C. Day, L.M. Hulse, The UK 9/11 evacuation study: analysis of survivors' recognition and response phase in WTC1, Fire Saf. J. 45 (1) (2010) 21–34.
[5] R.F. Fahy, How did people respond and evacuate in WTC twin towers in 2001? J. Dis. Res. 6 (6) (2011) 620–628.
[6] Y. Yoshida, Surveys and Analyses on human behavior in the New York World Trade Center disasters in 1993 and 2001, J. Dis. Res. 6 (6) (2011) 610–619.
[7] M.F. Sherman, M. Peyrot, L.A. Magda, R.R.M. Gershon, Modeling pre-evacuation delay by evacuees in World Trade Center Towers 1 and 2 on September 11, 2001: a revisit using regression analysis, Fire Saf. J. 46 (7) (2011) 414–424.
[8] R.F. Fahy, G. Proulx, Analysis of Published Accounts of the World Trade Center Evacuation, NIST NCRTAR 1-7A, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, 2005.
[9] D.A. Purser, M. Bensilum, Quantification of behaviour for engineering design standards and escape time calculations, Saf. Sci. 38 (2) (2001) 157–182.
[10] M. D'Orazio, S. Longhi, P. Olivetti, G. Bernardini, Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire, Autom. Constr. 52 (2015) 16–28.
[11] V. Oven, N. Cakici, Modelling the evacuation of a high-rise office building in Istanbul, Fire Saf. J. 44 (1) (2009) 1–15.
[12] T.J. Shields, K.E. Boyce, A study of evacuation from large retail stores, Fire Saf. J. 35 (1) (2000) 25–49.
[13] M. Liu, S.M. Lo, The quantitative investigation on people's pre-evacuation behavior under fire, Autom. Constr. 20 (5) (2011) 620–628.
[14] G.N. Hamilton, P.F. Lennon, J. O'Raw, Human behaviour during evacuation of primary schools: investigations on pre-evacuation times, movement on stairways and movement on the horizontal plane, Fire Saf. J. 91 (2017) 937–946.
[15] D. Nilsson, A. Johansson, Social influence during the initial phase of a fire evacuation -analysis of evacuation experiments in a cinema theatre, Fire Saf. J. 44 (1) (2009) 71–79.
[16] A.K. Chandra-Sekaran, A. Nwokafor, L. Shammas, C. Kunze, K.D. Mueller-Glaser, A disaster aid sensor network using ZigBee for patient localization and air temperature monitoring, Int. J. Adv. Internet Technol. 2 (2009) 68–80.
[17] T. Wang, R. Huang, L. Li, W. Xu, J. Nie, The application of the shortest path algorithm in the evacuation system, 2011 International Conference of Information Technology, Computer Engineering and Management Sciences, 2011, pp. 250–253.

[18] T. Tabirca, K.N. Brown, C.J. Sreenan, A dynamic model for fire emergency evacuation based on wireless sensor networks, Eighth International Symposium on Parallel and Distributed Computing, IEEE, 2009, pp. 29–36.
[19] P. Billon, E. Levin, Building peace with conflict diamonds, merging security and development in Sierra Leone, Dev. Change 40 (4) (2009) 693–715.
[20] A. Hokugo, K. Kubo, Y. Murozaki, An experimental study of confluence of two foot traffic flows in staircase, J. Archit., Plann. Environ. Eng., Trans. AIJ 358 (0) (1985) 37–43 (In Japanese).
[21] D.T. N. Takeichi, Y. Yoshida, T. Sano, T. Kimura, H. Watanabe, Y. Ohmiya, Characteristics of merging occupants in a staircase, eds. in: D.T. Gottuk, B.Y. Lattimer (Eds.), Fire Safety Science, Proceedings of the Eighth International Symposium, International Association for Fire Safety Science, London, 2006, pp. 591–598.
[22] E. Galea, G. Sharp, P. Lawrence, Investigating the representation of merging behavior at the floor-stair interface in computer simulations of multi-floor building evacuations, J. Fire Prot. Eng. 8 (4) (2008) 291–316.
[23] Y.C. Ding, L.Z. Yang, P. Rao, Investigating the merging behavior at the floor-stair interface of highrise building based on computer simulations, Pro. Eng. 62 (2013) 463–469.
[24] M. Yajima, T. Sano, H. Kadokura, A. Sekizawa, Walking speed relative density and merging ration of evacuees in staircase based on observation of a real evacuation fire drill in high-rise building, J. Environ. Eng. AIJ 80 (710) (2015) 315–322 (In Japanese).
[25] M. Zhong, C. Shi, X. Tu, T. Fu, L. He, Study of the human evacuation simulation of metro fire safety analysis in China, J. Loss Pre. Pro. Ind. 21 (3) (2008) 287–298.
[26] N. Pelechano, A. Malkawi, Evacuation simulation models: challenges in modeling high rise building evacuation with cellular automata approaches, Auto. Constr. 17 (4) (2008) 377–385.
[27] J.S. Milazzo, N.M. Rouphail, J.E. Hummer, D.P. Allen, The effect of pedestrians on the capacity of signalized intersections, Transportation Research Record 1646, Transportation Research Board, National Research Council, Washington DC, 1998.
[28] J.C. Chu, A.Y. Chen, Y.F. Lin, Variable guidance for pedestrian evacuation considering congestion, hazard, and compliance behavior, Trans. Res. Part C 85 (2017) 664–683.
[29] L.F. Henderson, The statistics of crowd fluids, Nature 229 (5284) (1971) 381–383.
[30] G.C. Lovas, Modeling and simulation of pedestrian traffic flow, Trans. Res. B 28 (6) (1994) 429–443.
[31] K. Takahashi, T. Tanaka, S. Kose, et al., An evacuation model for use in fire safety design of buildings, in: T. Wakamatsu, Y. Hasemi, A. Sekizawa, et al. (Eds.), Fire Safety Science–Proceedings of the second International Symposium, International Association for Fire Safety Science, 1989, pp. 551–560.
[32] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, Nature 407 (6803) (2000) 487–490.
[33] M. Xu, Y. Wu, P. Lv, H. Jiang, M. Luo, Y. Ye, miSFM: on combination of mutual information and social force model towards simulating crowd evacuation, Neuro 168 (2015) 529–537.
[34] M. Haghani, M. Sarvi, Social dynamics in emergency evacuations: disentangling crowd's attraction and repulsion effects, Physica A 475 (2017) 24–34.
[35] D. Helbing, M. Isobe, T. Nagatani, K. Takimoto, Lattice gas simulation of experimentally studied evacuation dynamics, Phys. Rev. E 67 (6) (2003) 067101.
[36] X. Guo, J. Chen, S. You, J. Wei, Modeling of pedestrian evacuation under fire emergency based on an extended heterogeneous lattice gas model, Physica A 392 (9) (2013) 1994–2006.
[37] J.P. Yuan, Z. Fang, Y.C. Wang, S.M. Lo, P. Wang, Integrated network approach of evacuation simulation for large complex building, Fire Saf. J. 44 (2) (2009) 266–275.
[38] S.M. Lo, Z. Fang, P. Lin, G.S. Zhi, An evacuation model: the SGEM package, Fire Saf. Sci. 39 (3) (2004) 169–190.
[39] L. Fu, W. Song, W. Lv, X. Liu, S. Lo, Multi-grid simulation of counter flow pedestrian dynamics with emotion propagation, Simul. Model. Pract. Theory 60 (2016) 1–14.
[40] N. Chooramun, P.J. Lawrence, E.R. Galea, An agent based evacuation model utilising hybrid space discretisation, Saf. Sci. 50 (8) (2012) 1685–1694.
[41] J. Joo, N. Kim, R.A. Wysk, L. Rothrock, Y.J. Son, Y.G. Oh, S. Lee, Agent-based simulation of affordance-based human behaviors in emergency evacuation, Simul. Model. Pract. Theory 32 (2013) 99–115.
[42] J. Ma, S.M. Lo, W.G. Song, Cellular automaton modeling approach for optimum ultra high-rise building evacuation design, Fire Saf. J. 54 (2012) 57–66.
[43] K. Huang, X. Zheng, Y. Cheng, Y. Yang, Behavior-based cellular automaton model for pedestrian dynamics, Appl. Math. Comp. 292 (2017) 417–424.
[44] L. Luo, Z. Fu, H. Cheng, L. Yang, Update schemes of multi-velocity floor field cellular automaton for pedestrian dynamics, Physica A 491 (2018) 946–963.
[45] P.A. Thompson, E.W. Marchant, Testing and application of the computer model 'SIMULEX', Fire Saf. J. 24 (1995) 149–166.
[46] B.M. Levin, EXITT: a simulation model of occupant decisions and actions in residential fires, in: T. Wakamatsu, Y. Hasemi, A. Sekizawa, P.G. Seeger, P.J. Pagni, C.E. Grant (Eds.), Fire Safety Science–Proceedings of the second International Symposium, International Association for Fire Safety Science, 1988, pp. 561–570.
[47] E.R. Galea, J.M.P. Galparsoro, A computer based simulation model for the prediction of evacuation from mass transport vehicles, Fire Saf. J. 22 (4) (1994) 341–366.
[48] S. Gwynne, E.R. Galea, P.J. Lawrence, L. Filippidis, Modeling occupant interaction with fire conditions using the building EXDOUS evacuation model, Fire Saf. J. 36 (4) (2001) 327–357.
[49] T. Gasparotto, A. Collin, P. Boulet, G. Pianet, A. muller, An Emergency egress model based on a macroscopic continuous approach, https://www.thunderheadeng.com/files/com/FEMTC2016/files/d2-02-gasparotto/gasparotto-paper.pdf/, 2016.
[50] M.H. Nguyen, T.V. Ho, J.D. Zucker, Integration of smoke effect and blind evacuation strategy (SEBES) within fire evacuation simulation, Simul. Model. Pract. Theory 36 (2013) 44–59.
[51] E. Ronchi, D. Nilsson, Fire evacuation in high-rise buildings: a review of human behaviour and modelling research, Fire Sci. Rev. 2 (7) (2013) 7 http://www.firesciencereviews.com/content/2/1/7/.
[52] J. Koo, Y.S. Kim, B.I. Kim, K.M. Christensen, A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation, Expert Sys. Appl. 40 (2) (2013) 408–417.
[53] E. Ronchi, D. Nilsson, Modelling total evacuation strategies for high-rise buildings, Build. Simul. 7 (1) (2014) 73–87.
[54] Y. Ding, L. Yang, F. Weng, Z. Fu, P. Rao, Investigation of combined stairs elevators evacuation strategies for high rise buildings based on simulation, Simul. Model. Pract. Theory 53 (2015) 60–73.
[55] K.H. Hsiung, W.J. Wen, S.W. Chien, B.J. Shih, W.H. Hsiao, A research of the elevator evacuation performance for Taipei 101 financial center, 6th International Conference on Performance-Based Codes and Fire Safety Design Methods, Tokyo, Japan, Waseda University, 2006, pp. 213–225.
[56] S.W. Chien, W.J. Wen, A research of the elevator evacuation performance and strategies for Taipei 101 financial center, J. Disa. Res. 6 (6) (2011) 581–590.
[57] Y.J. Liao, G.X. Liao, S.M. Lo, Influencing factor analysis of ultra-tall building elevator evacuation, Proc. Eng. 71 (2014) 583–590.
[58] J. Chen, J. Ma, S.M. Lo, Event-driven modeling of elevator assisted evacuation in ultra high-rise buildings, Simul. Model. Pract. Theory 74 (2017) 99–116.
[59] G. Proulx, Movement of people: the evacuation timing, The SFPE Handbook of Fire Protection Engineering, third ed., Society of Fire Protection Engineers, Bethesda, MD, 2002, pp. 341–366 Chapter 3, section 13.
[60] R.D. Peacock, B.L. Hoskins, E.D. Kuligowski, Overall and local movement speeds during fire drill evacuations in buildings up to 31stories, Saf. Sci. 50 (8) (2012) 1655–1664.
[61] R.F. Fahy, Calculation methods for egress prediction, editor-in-chief, in: AE Cote (Ed.), The SFPE Handbook of Fire Protection Engineering, Chapter 2, Section 4, Quincy, National Fire Protection Association, NFPA, Massachusetts, 2008, pp. 49–68.
[62] E.D. Kuligowski, R.D. Peacock, P.A. Reneke, E. Wiess, C.R. Hagwood, K.J. Overholt, R.P. Elkin, J.D. Averill, E. Ronchi, B.L. Hoskins, M. Spearpoint, Movement On Stairs During Building Evacuations, NIST Technical Note1839, National Institute of Standards and Technology, USA, 2015, p. 122 available online at: http://dx.doi.org/10.6028/NIST.TN.1839/.
[63] J. Ma, W.G. Song, W. Tian, S.M. Lo, G.X. Liao, Experimental study on an ultra high-rise building evacuation in China, Saf. Sci. 50 (8) (2012) 1665–1674.
[64] G.Y. Wu, M. Mizuno, C.K. Ke, Study on mass evacuation during fire drills in a stairwell of super high-rise buildings, Bull. Japan Associ. Fire Sci. Eng. 67 (2) (2017) 37–49.
[65] The Building Center of Japan, Guideline of building safety evacuation, 1995.

[66] Architecture and Building Research Institute of Taiwan, The Technical Handbook of Performance Validation of Building Fire Safety Evacuation, ABRI, Taiwan, 2006 (In Chinese).
[67] G.Y. Wu, H.C. Huang, Modeling the emergency evacuation of the high rise building based on the control volume model, Saf. Sci. 73 (5) (2015) 62–72.
[68] G.Y. Wu, S.W. Chien, Y.T. Huang, Modeling the occupant evacuation of the mass rapid transit station using the control volume, Build. Environ. 45 (10) (2010) 2280–2288.
[69] Z.M. Fang, W.G. Song, Z.J. Li, W. Tian, W. Lv, J. Ma, X. Xiao, Experimental study on evacuation process in a stairwell of a high-rise building, Build. Environ. 47 (2012) 316–321.
[70] F. Huo, W. Song, L. Chen, C. Liu, K.M. Liew, Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building, Saf. Sci. 86 (2016) 165–173.
[71] S.J. Melinek, S. Booth, An analysis of evacuation times and the movement of crowds in buildings. Current Paper CP 96/75, Building research establishment, Fire research station, Borehamwood, UK, 1975.
[72] D.J. Low, Following the crowd, Nature 407 (6803) (2000) 465–466.