Front. Eng. Manag. 2021, 8(1): 135–147
https://doi.org/10.1007/s42524-020-0125-1

RESEARCH ARTICLE

Shu CHEN, Menghan SHANG, Jianping WANG

Evacuation strategies for vertical ship lift during initial fire: Integrated application of stairs and elevators

Abstract Vertical ship lifts (VSLs) are widely used in navigation facilities worldwide because of their efficiency and low cost. Although several researchers have investigated fire evacuation strategies for reducing potential safety hazards in VSLs, an effective and integrated application of stairs and elevators when a fire occurs in a VSL is necessary. Several evacuation routes were analyzed according to VSL structure and evacuation times in this study. Objective function corresponding to the minimum vertical evacuation time and related simulation model was subsequently developed to obtain a cooperative evacuation plan considering different numbers of evacuees. The Three Gorges ship lift was used as an example, and simulation results indicate that number of evacuees and exit selection are the main influencing factors of the total evacuation time in the stair- and elevator-coordinated evacuation mode. Furthermore, the distance between people trapped in ship reception chamber and evacuation exits affects evacuees' choice of exits. The proposed model can provide a theoretical reference for evacuation research during initial fire events in VSLs.

Keywords vertical ship lift, initial fire, fire evacuation, numerical simulation, stair, elevator

Received October 4, 2019; accepted June 6, 2020

Shu CHEN, Menghan SHANG
Hubei Key Laboratory of Construction and Management in Hydropower Engineering, College of Hydraulic & Environmental Engineering, China Three Gorges University, Yichang 443002, China

Jianping WANG (✉)
College of Economics & Management, China Three Gorges University, Yichang 443002, China
E-mail: wjp@ctgu.edu.cn

This study is sponsored by the National Natural Science Foundation of China (Grant No. 51609128) and the Open Foundation of Hubei Key Laboratory of Construction and Management in Hydropower Engineering (Grant No. 2019KSD06).

1 Introduction

Ship lifts are a type of navigation facility that drives ships up and down using mechanical devices to overcome decreases in water levels (Chen et al., 2018). Vertical ship lifts (VSLs) are navigation facilities that improve guidance efficiency and provide passage for ships required to pass through a dam. As the name implies, VSL performs the same function for a ship that an elevator performs for people. VSLs have been adopted worldwide, especially in China (e.g., Three Gorges ship lift (TGSL)), due to demand for low water consumption, high dam passing speeds, and large lifting heights (Yang and Lu, 2017). The rapid development of China's economy has remarkably increased the demand for shipping and caused widespread application of VSLs.

Ships driven by VSLs are primarily passenger ships that have a high risk of fire occurrence because they carry a large amount of flammable materials, such as kitchen supplies and quilts (Wang et al., 2018). The main structure of VSLs includes ship reception chamber and bearing tower column, which is a closed internal space. Evacuation may become challenging in the event of a fire, leading to several casualties and property losses (Li et al., 2018). Dynamic braking process of VSLs affects the evacuation. Although regulators have successively issued relevant documents on VSL evacuation, such as Code for Fire Protection Design of Hydropower Projects (2014) and Design Code for Ship Lifts (2016), the major disadvantages of VSLs are ultrahigh tower leakproof structure, densely distributed population, and dynamic braking process of operation, which impedes the spread of smoke and increases difficulty in evacuation once a fire breaks out. Given that fire evacuation of VSLs is difficult for regulators, the optimal evacuation route for occupants and improving fire evacuation performance are critical in ensuring navigation safety (LaDue and Tetreault, 2017; Chen et al., 2019).

Efficient evacuation plans are needed during fire events. Many scholars have recently investigated fire evacuation of ultrahigh buildings (Butler et al., 2017; Kong et al., 2017). In the case of multistory buildings, both elevators and stairs can be used as transportation modes (Ma et al., 2012a). However, in the event of an evacuation, occupants can only evacuate using stairs, as required by current codes for building fire protection. Limited stairwell capacity and long distances to exits may lead to congestion and long delays in the evacuation of multistory buildings, such as VSLs (Ma et al., 2012b). The attack on the World Trade Center has led to the use of elevators for high-rise building evacuations. Furthermore, international building codes have recently allowed the use of properly protected fire elevators during building evacuations (NIST, 2008). The fire development process is generally divided into three stages, namely, initial, overall development, and fire abatement stages. A large amount of smoke is produced with the emergence of these three stages. The leakproof structure of VSLs impedes the spreading of smoke. Evacuees can have difficulty in breathing or may even suffocate (Wang et al., 2020). Hence, the initial stage is a key period in VSL evacuation because the fire in this stage has a small burning range, which can facilitate the safe evacuation of people in buildings, rescuing important materials, and firefighting. If the fire-induced growth reaches the flashover stage, then lives of people who have not been evacuated may be threatened. The initial stage of fire involves minimal smoke, which slightly influences the elevator operation. Therefore, a coordinated strategy involving stairs and elevators should be used in the initial fire stage to perform rapid evacuations.

Notably, combustibles in ships may cause fires during the lifting process via VSL. Once a fire occurs in the ship reception chamber at any elevation, a fire evacuation warning is issued and lifting of the chamber is immediately stopped (Chen et al., 2019). The number of people in the ship reception chamber may vary depending on passenger capacities of different passenger ships, leading to uncertainties in the number of evacuees and the elevation at which evacuation should be initiated. Furthermore, VSLs typically have two evacuation exits at different heights for occupants to choose from during an evacuation. Therefore, evacuees' choice of evacuation exits must also be considered. Factors including dynamic braking process of VSLs, the number of evacuees and the uncertainty of evacuation exit choices increase the complexity of evacuation. The optimal allocation of people using different evacuation strategies and a rational plan concerning evacuation routes for different evacuation scenarios must be urgently realized. Collaborative evacuation times for different numbers of evacuees and various parking elevations must be compared and analyzed to improve the emergency evacuation efficiency of VSLs.

Reasonable allocation of the number of people using stairs and elevators is related to evacuation speed. In the case of staircase evacuation, many factors, such as stair size, population density (Huo et al., 2016), and slope (Graat et al., 1999; Sheehan and Gottschall, 2012), affect the speed of pedestrian movement. Nontraditional evacuation methods for ultrahigh buildings include elevators, rope ladders, and helicopters (Chen et al., 2016), but some of the methods, except that using elevators, have various constraints. Such nontraditional evacuation methods are unsuitable for massive evacuation because rope ladders are insufficiently long and the space of ultrahigh buildings is limited for helicopter parking. Therefore, using elevators for staircase evacuation is recommended in ultrahigh buildings. Factors such as the number of available elevators, number of evacuees carried in the elevator at each run (Ma et al., 2013), and traveling time (Klote, 1993), affect the elevator evacuation efficiency. Performing evacuation via elevators also has the advantages of increased mobility for people with disabilities (Koo et al., 2013; Butler et al., 2017) and high potential for shortening the total evacuation time (Lu et al., 2012). By contrast, the disadvantages of elevator evacuation include poor reliability due to smoke (Black, 2009) and spreading of fire due to piston effect (Klote and Tamura, 1986).

Considering that evacuation using stairs or elevators alone is not the best evacuation method, many researchers have recommended the implementation of strategies that combine stairs and elevators for evacuation to optimize the evacuation efficiency. An evacuation strategy combining high-rise building stairs with elevators was proposed to minimize the evacuation time, and the findings indicated that the percentage of the number of people evacuated using the elevator is nearly constant when the number of evacuation layers is fixed (Ding et al., 2015). The authors of another study used a method based on simulation optimization to develop an evacuation strategy involving the use of stairs and elevators in high-rise buildings; the simulation results indicated that the efficiency of evacuation involving stairs and elevators is 41% higher than the findings of traditional evacuation (Ding et al., 2017). Wang et al. (2014) simulated three different evacuation scenarios with STEPS according to fire characteristics of ultrahigh buildings and found that the end of the evacuation is marked by the evacuation to the outdoor space on the ground floor of the building and elevator evacuation has an important effect on the improvement of evacuation efficiency. Cao et al. (2013) analyzed the feasibility of elevator evacuation in ultrahigh buildings and demonstrated that the total evacuation time is at the minimum when the number of people evacuated using elevators accounts for 40% of the total evacuees. Hu and Yang (2007) used the ELVAC and SIMULEX models to analyze the impact of the number of elevators and personnel distribution on the elevator evacuation and determined that the hybrid evacuation method combining stairs and elevators can effectively improve the evacuation efficiency. Guo et al. (2018) established a mathematical model for the evacuation process of high-rise buildings and obtained the optimal parking floor of the elevator with the shortest collaborative evacuation time. Chen et al. (2016) established three different evacuation scenarios to investigate the distribution of people in high-rise building evacuations and found that 30% and 60% of people should use the elevator to evacuate when evacuees are located on floors 30–48 and 50–66, respectively.

The standard procedure during a fire emergency is to evacuate downward inside the building, except if conditions in the lower floors are untenable; in which case, evacuation is performed upward to the roof (Ronchi and Nilsson, 2013). However, upward evacuation is a non-ideal strategy because of the limited space on the roof of buildings. Although traditional studies on the collaborative evacuation involving stairs and elevators provide theoretical support and valuable experience for further investigations, only the condition of downward evacuation inside the building to the ground exit is considered while ignoring the possibility of multiple-exit selection during the evacuation. Furthermore, facilities considered in traditional approaches are stationary, whereas the ship reception chamber of VSLs is dynamic. The dynamic braking process of VSL affects the evacuees' choice of evacuation exits. Hence, traditional methods are unsuitable for VSL evacuation for the VSL evacuation exits are located at different vertical elevations. The varying distances between the evacuated people and the exits under different conditions allows evacuees to evacuate from different evacuation exits. Therefore, the problem of suitable exit selection must be resolved.

Numerical simulation is used in this study to consider evacuation strategies involving the use of both stairs and elevators of VSLs. First, several evacuation routes are determined by analyzing the VSL structure. Second, the evacuation time related to stairs and elevators of different evacuation routes is calculated; on the basis of which, the objective function of the minimum vertical evacuation time is established. Finally, Pathfinder tool is used to establish an evacuation scene for the considered case of Three Gorges VSL via the numerical simulation of three different scenarios involving different numbers of evacuees. Factors affecting the vertical evacuation time are subsequently identified on the basis of the simulation results. This article primarily provides an empirical basis for the initial-fire evacuation strategy of VSLs.

2 Methodology

The proposed methodology can be defined as follows. Evacuation routes are analyzed in accordance with the building structure, as described in Section 2.1. The relation between parameters related to the evacuation speed and time is subsequently established and the objective function considering the minimum vertical evacuation time is determined, as discussed in Section 2.2. Finally, the numerical simulation performed according to the flowchart is described in Section 2.3.

2.1 Evacuation routes

VSL, primarily composed of the tower column and the ship reception chamber, is a steel structure used to carry the ship over a high dam. The tower column is arranged symmetrically on both sides and divided into several floors (F_1, F_2,…, F_n). Each floor has an elevator entrance and a staircase exit. The ship reception chamber is located in the middle of the ship lift and surrounded by four tower columns. Stereogram and planform of VSLs are illustrated in Fig. 1.

Each tower has upstream and downstream evacuation exits. The upstream evacuation exit is connected to the top of the dam, whereas the downstream evacuation exit located between the lowest and highest water levels is linked to the shore road and indirectly connected to the ground. When a fire breaks out in the ship reception chamber, the movement of it is stopped immediately and

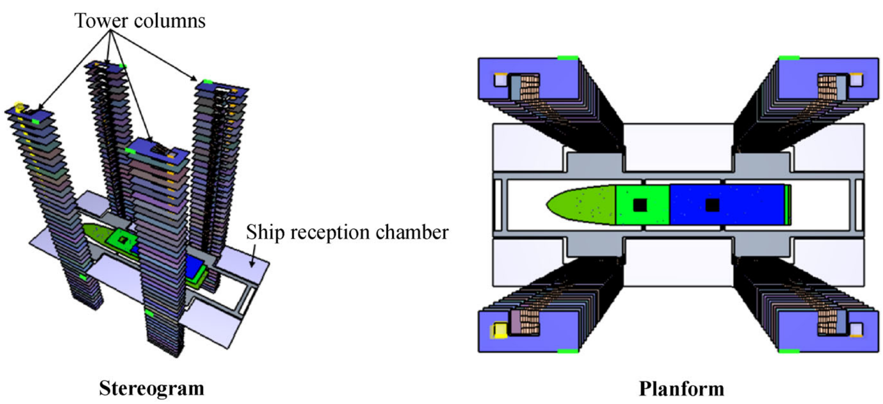

Fig. 1 Structure of the ship lift.

evacuees must exit using staircases or elevators. The evacuation path is illustrated in Fig. 2. Assuming that the total number of evacuees, proportion of evacuees using staircases for evacuation, and proportion of people moving up the stairs during the evacuation are M; α, $\alpha \in [0, 1]$; and β, $\beta \in [0, 1]$, respectively, then the number of evacuees using elevators for evacuation, number of people moving up the stairs, and number of people moving down the stairs are $M(1-\alpha)$, $M\alpha\beta$, and $M\alpha(1-\beta)$, respectively.

2.2 Evacuation time

The total vertical evacuation time is the larger value between the staircase and elevator evacuation times during the evacuation:

$$T_{\text{evacuation}} = \text{Max}(T_{\text{stair}},\ T_{\text{elevator}}). \tag{1}$$

The proportion of people using stairs or elevators, proportion of people using stairs to move up or down, and parking elevation are fundamental factors that influence the evacuation time. Thus, a reasonable value for α must be set initially. The value of β changes with the parking elevation of the ship reception chamber. β is equal to 0 when people evacuate by moving downward to the tower column and the staircase evacuation time is equal to the time of evacuation movement toward the tower column. Conversely, β is equal to 1 when the staircase evacuation time is equal to the time of evacuation via stairs to move up. Therefore, adjusting α and β is crucial in obtaining the minimum vertical evacuation time.

2.2.1 Evacuation speed

Field observation and experimental research results have demonstrated that the walking speed of people is affected by crowd density (Pauls, 1987; Smith, 1995), which is the basic parameter of emergency evacuation that reflects the compactness of the population distribution. The walking speed is high when the crowd density is low but low in a crowded region. Thus, the speed of a crowd moving up or down the stairs is a function of the crowd density. The crowd density (D) can be expressed as follows (Fang et al., 2003):

$$D = \frac{QA_{\text{p}}}{WL_{\text{s}}}, \tag{2}$$

where Q denotes the total number of pedestrians, A_{p} denotes the horizontal projection area of a single person (m^2), W denotes the stream width (m), and L_{s} denotes the length of flow (m). The movement speed of people in dense population is also affected by the structural arrangement of passageways (Lam and Cheung, 2000). The walking speed in a horizontal passageway is considerably different from that in a staircase. The stair movement involves more complicated variables than motion in a horizontal plane. Fruin (1971a; 1971b) defined equations related to the walking speed and crowd density under different conditions of unidirectional, bidirectional, and multidirectional flows, and Li et al. (2014) provided different evacuation models. The speed of moving up and down the stairs can be expressed as follows:

(i) Speed of moving up the stairs :

$$v_{\text{up}} = 0.564 - 0.0765D, \tag{3}$$

(ii) Speed of moving down the stairs :

$$v_{\text{down}} = 0.6502 - 0.0972D. \tag{4}$$

2.2.2 Staircase evacuation time

Tower columns are identified as evacuation safe areas when a fire breaks out in the ship reception chamber. Evacuation layers are arranged with intervals of 3.5 m in the vertical direction of the tower column. According to the principle of parking, evacuees select the corresponding

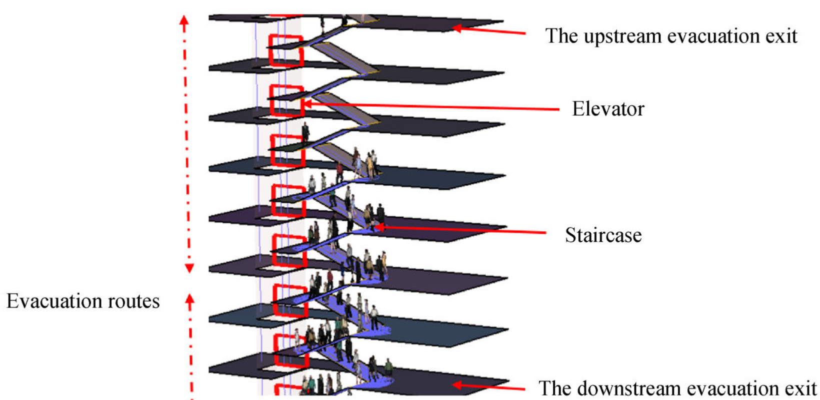

Fig. 2 Evacuation routes (color blue represents the evacuation trajectory of people on staircases and elevators).

evacuation layer to exit when the parking elevation is H. The relationship among the parking elevation, corresponding evaluation layer, and evacuation layer elevation (h) is discussed in detail.

When $H = h$, the ship reception chamber is parked at the same elevation as the evacuation layer and evacuees can exit directly from the evacuation layer.

When $h_x < H < h_{x+1}$, the ship reception chamber is parked between evacuation layers F_x and F_{x+1}, the corresponding elevations of these evacuation layers are h_x and h_{x+1}, respectively, and evacuees select layer F_{x+1} to exit from.

Assume that the elevation of downstream and upstream evacuation exits are H' and H'', respectively. If the parking elevation is below the downstream evacuation exit, then occupants will evacuate via the downstream evacuation exit. If the parking elevation is between the upstream and downstream evacuation exits, then occupants can evacuate via the upstream or downstream evacuation exit. The evacuation time via staircase can be calculated by determining the higher value between the evacuation times of crowds moving up and down the stairs.

When $H' < h < H''$, crowds can evacuate via the upstream or downstream evacuation exit. The evacuation time up the stairs can be obtained as follows:

$$T_{\mathrm{up}} = \frac{\alpha\beta M}{KS} + \frac{H'' - h}{\sin\gamma \cdot v_{\mathrm{up}}}. \tag{5}$$

The evacuation time down the stairs can be obtained as follows:

$$T_{\mathrm{down}} = \frac{\alpha(1-\beta)M}{KS} + \frac{h - H'}{\sin\gamma \cdot v_{\mathrm{down}}}, \tag{6}$$

where S is the width of stairs (m), K is the staircase passing coefficient, and γ is the slope of the stairs. Therefore, the time of evacuation via staircase is:

$$T_{\mathrm{stair}} = \mathrm{Max}(T_{\mathrm{up}},\ T_{\mathrm{down}}),\ H' < h < H''. \tag{7}$$

In the optimal case, T_{up} is equal to T_{down}. Thus,

$$T_{\mathrm{up}} = T_{\mathrm{down}} = \frac{1}{2}\left(\frac{h - H'}{\sin\gamma \cdot v_{\mathrm{down}}} + \frac{H'' - h}{\sin\gamma \cdot v_{\mathrm{up}}} + \frac{\alpha M}{KS}\right), \tag{8}$$

$$\beta = \frac{1}{2}\left(\frac{h - H'}{\sin\gamma \cdot v_{\mathrm{down}}} - \frac{H'' - h}{\sin\gamma \cdot v_{\mathrm{up}}}\right)\frac{KS}{\alpha M} + \frac{1}{2}. \tag{9}$$

When $h < H'$, people can opt to move up the stairs to the downstream evacuation exit. Thus,

$$T_{\mathrm{up}_1} = \frac{\alpha\beta M}{KS} + \frac{H' - h}{\sin\gamma \cdot v_{\mathrm{up}}}, \tag{10}$$

$$\beta = 1. \tag{11}$$

The total time of evacuation via staircase can be expressed as:

$$T_{\mathrm{stair}} = \begin{cases} \mathrm{Max}(T_{\mathrm{up}},\ T_{\mathrm{down}}),\ H' < h < H'' \\ T_{\mathrm{up}_1} = \dfrac{\alpha\beta M}{KS} + \dfrac{H' - h}{\sin\gamma \cdot v_{\mathrm{up}}},\ h < H' \end{cases}. \tag{12}$$

2.2.3 Elevator evacuation time

The elevator is assumed to stop at the evacuation layer constantly in the process of elevator evacuation. Vertical distances between the evacuation layer and the two different evacuation exits must be compared, and the evacuation exit nearest to the elevator is selected. The elevator evacuation time in this study includes the vertical operation time and the time taken by people to leave the elevator or the leveling time (t_h). Given that the proportion of people evacuated via the elevator is ($1 - \alpha$) and the number of people using the elevator during each run is Z, the number of times the elevator operates (N) can be calculated. Given that N is an integer, the elevator must be operated even when the number of passengers is less than the maximum capacity of the elevator. Therefore, the number of operation times (N) can be defined as:

$$N = \left\lceil \frac{(1-\alpha)\cdot M}{Z} \right\rceil. \tag{13}$$

The elevator evacuation operation commonly includes acceleration, uniform speed, and deceleration stages from start to stop. However, the elevator travel time is related to the size of the actual running distance. The elevator movement for a small distance is illustrated in Fig. 3. The motion starts with constant acceleration and ends with uniform deceleration. The deceleration has the same magnitude as the acceleration, and the total acceleration time is equal to the total deceleration time. The time to accomplish the constant acceleration movement is expressed as follows:

$$t_1 = \frac{v_{\mathrm{normal}}}{a}, \tag{14}$$

where v_{normal} is the normal speed of the elevator and a is the accelerated velocity of the elevator. The distance traveled during the entire process ($2S_1$) is:

$$2S_1 = \frac{(v_{\mathrm{normal}})^2}{a}. \tag{15}$$

When the actual operating distance of the elevator $S_{\mathrm{T}} < 2S_1$, the travel time is:

$$T_{\mathrm{all}_1} = 2\sqrt{\frac{S_{\mathrm{T}}}{a}} + t_h. \tag{16}$$

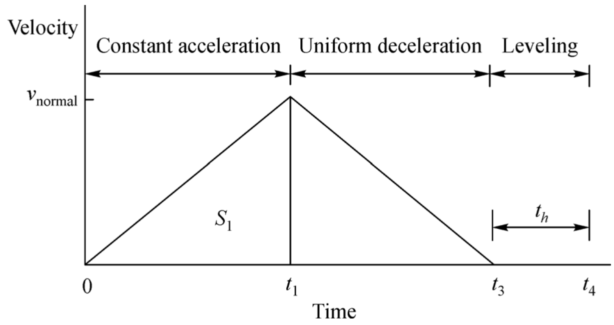

Fig. 3 Short distance travel.

The elevator motion for a large distance is illustrated in Fig. 4. The motion starts with constant acceleration, followed by constant velocity motion, and ends with uniform deceleration.

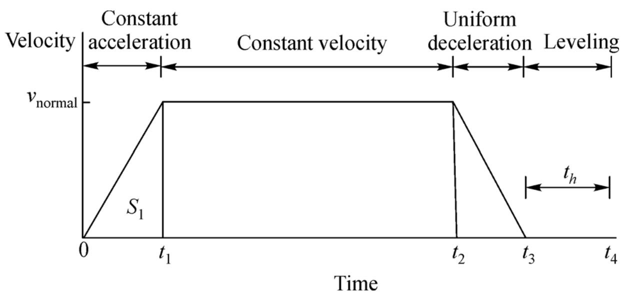

Fig. 4 Long distance travel.

When $S_{\mathrm{T}} > 2S_1$, the travel time is:

$$T_{\mathrm{all}_2} = 2\frac{v_{\text{normal}}}{a} + \frac{S_{\mathrm{T}} - \frac{(v_{\text{normal}})^2}{a}}{v_{\text{normal}}} + t_h. \tag{17}$$

Thus, the total elevator evacuation time is:

$$T_{\text{elevator}} = \begin{cases} N\left(2\sqrt{\frac{S_{\mathrm{T}}}{a}} + t_h\right), & S_{\mathrm{T}} < \frac{(v_{\text{normal}})^2}{a} \\ N\left(2\frac{v_{\text{normal}}}{a} + \frac{S_{\mathrm{T}} - \frac{(v_{\text{normal}})^2}{a}}{v_{\text{normal}}} + t_h\right), & S_{\mathrm{T}} > \frac{(v_{\text{normal}})^2}{a} \end{cases}. \tag{18}$$

Then, the vertical evacuation time is:

$$T_{\text{evacuation}} = \mathrm{Max}(T_{\text{stair}},\ T_{\text{elevator}}). \tag{19}$$

2.3 Evacuation simulation

α and β are initially considered as independent variables to determine the distribution coefficient of evacuation. The minimum vertical evacuation time is then considered the target, and the parking elevation H and number of evacuees M are constantly updated. Finally, the resulting data are analyzed, and the optimal distribution of evacuation crowd flow is selected. The simulation process is illustrated in Fig. 5. A step-by-step description of this logic is presented as follows.

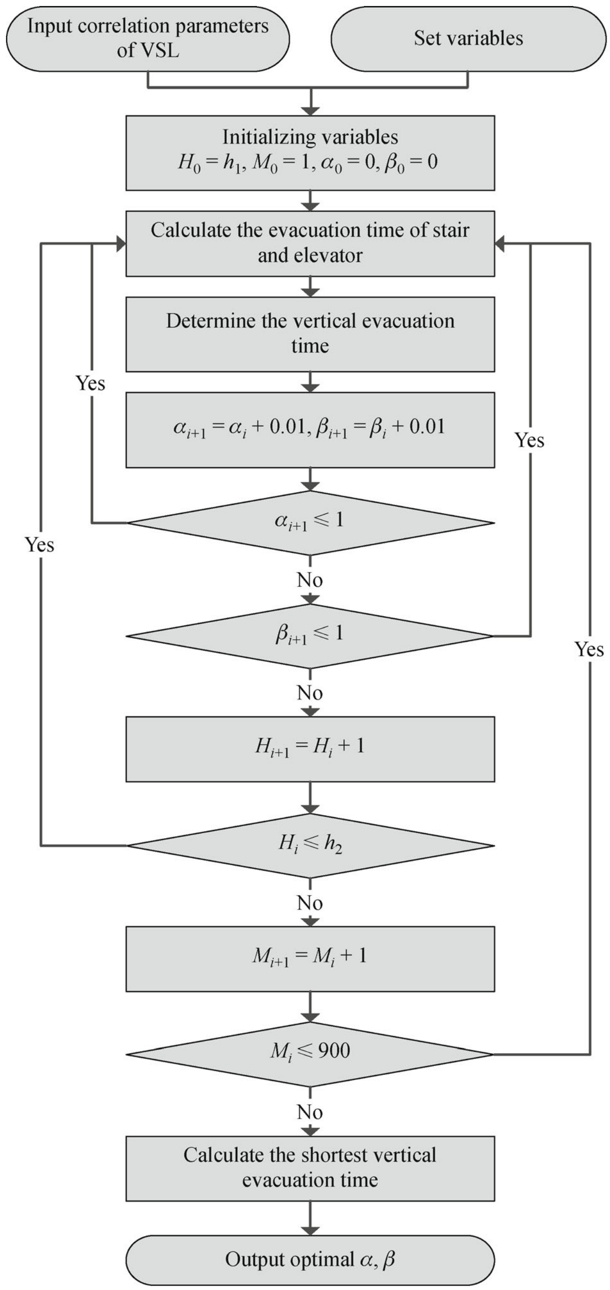

Fig. 5 Simulation process flow.

Step 1: Establish relevant parameters, including upstream exit elevation H''; downstream platform elevation H'; downstream navigable water level h_1; upstream water level h_2, with $h_1 < H' < h_2 < H''$; number of evacuees M, with $M \in [1, 900]$; parking elevation H of the ship reception chamber, with $H \in [h_1, h_2]$; proportion of people using stairs α, with $\alpha \in [0, 1]$; and proportion of people evacuating via stairs to the upstream platform β, with $\beta \in [0, 1]$.

Step 2: Initialize H, M, α, and β with $H_0 = h_1$, $M_0 = 1$, $\alpha_0 = 0$, and $\beta_0 = 0$.

Step 3: Obtain staircase and elevator evacuation times T_{stair} and T_{elevator}.

Step 4: Compare T_{stair} and T_{elevator} and set the maximum of the two values as the vertical evacuation time $T_{\text{evacuation}}$.

Step 5: Update H and M with $H_{i+1} = H_i + 0.1$ and $M_{i+1} = M_i + 1$, respectively, where i is the number of traversal times. α and β vary with M and H, $\alpha_{i+1} = \alpha_i + 0.01$ and $\beta_{i+1} = \beta_i + 0.01$. Hence, different parking elevations and number of evacuees correspond to various evacuation methods. If $\alpha_{i+1} \leqslant 1$ and $\beta_{i+1} \leqslant 1$, then Steps 3 to 5 are repeated; otherwise, Step 6 is performed.

Step 6: Calculate the minimum vertical evacuation time $\min T_{\text{evacuation}}(\alpha_i, \beta_i)$ to obtain the corresponding parking elevation, number of evacuees, and corresponding optimal proportion.

Step 7: If $H_{i+1} = h_2$ and $M_{i+1} \leqslant 900$, then Steps 3 to 7 are repeated; otherwise, the simulation is stopped.

3 Case study

3.1 Case description

TGSL is the world's largest fully balanced VSL with gear and rack. The elevation of upper and lower evacuation exits of TGSL is 84 and 185 m, respectively, and the navigable water level ranges from 62 to 175 m. Four structural towers are present inside the ship lift, and each tower column is provided with a safe evacuation staircase and an elevator. The elevator runs at a speed of 2.5 m/s, the full load number of the elevator is 19, and the stair width is 150 cm.

The ultimate carrying capacity of the ship passing through the dam is 900 people. Evacuation crowds are assumed to enter the four towers evenly for evacuation. The evacuation scene is established using Pathfinder to simulate the evacuation process scientifically. Pathfinder, developed by Thunderhead Engineering in the USA, is an evacuation simulator based on the ingress, egress, and movement of people, which provides simulation design and execution with graphical user interface and analysis results of first-level three-dimensional visualization. Many scholars have recently used Pathfinder to solve evacuation problems. Ding and Yang (2013) used Pathfinder to model and simulate the evacuation process of public buildings; the results showed that the relation between the evacuation time and the number of people is nearly a monotonically increasing linear function when the number of people on each floor exceeded a certain limit. Bao (2011) utilized the Pathfinder software to simulate the evacuation process of large underground banquet halls and provided reasonable suggestions on the basis of the simulation results to enhance the fire safety of large banquet halls. Fang et al. (2012) considered the influence of the stair design on the building plane evacuation using the Pathfinder software.

Evacuation strategies involving the use of both stairs and elevators in VSLs are investigated in this study through the Pathfinder software. The evacuation scene considering the ship lift structure is initially established and the specific information of relevant factors, such as the number of people, elevators, and stairs, are regarded as input. The dynamic simulation is then performed according to the input information. For simplicity, the number of evacuees of one tower in the simulation is set as 225, 125, and 50 for cases 1, 2, and 3, respectively. Assuming that the elevator runs at full capacity each time, the velocity is based on the results of the staircase evacuation velocity discussed in Section 2.2.1.

The density of evacuated people in the tower during the simulation process is illustrated in Fig. 6. The upper part of the figure demonstrates that evacuated people leave the ship reception chamber first and subsequently enter the column tower when the fire occurs; at this time, the population density is large at the exit of the ship reception chamber. The lower part of the image shows that the population density is large in the staircase in the vertical evacuation process.

3.2 Staircase evacuation time

Based on the assumptions in Sections 2.3 and 3.1, the evacuation process was smoothly simulated by the software. The staircase evacuation time is illustrated in Fig. 7. Notably, when α is fixed irrespective of the number of evacuees, the staircase evacuation time first reduces, then increases, and finally reduces with the increase in the parking elevation. The time taken to traverse stairs increases as α increases when the number of occupants is fixed. Moreover, the time is minimized at parking elevation of 85 m in all the three cases; however, the maximum time differs. The maximum value of time tends to decrease suddenly, and the smaller the α, the more obvious the tendency.

Although some differences exist, the three cases follow a general trend. The obtained optimal staircase evacuation time corresponds to cases when α is 8%, 8%, and 24%, respectively, with evacuees set as 225, 125, and 50. Although the number of evacuees varies, the minimum staircase evacuation time is obtained always at the parking elevation of 85 m.

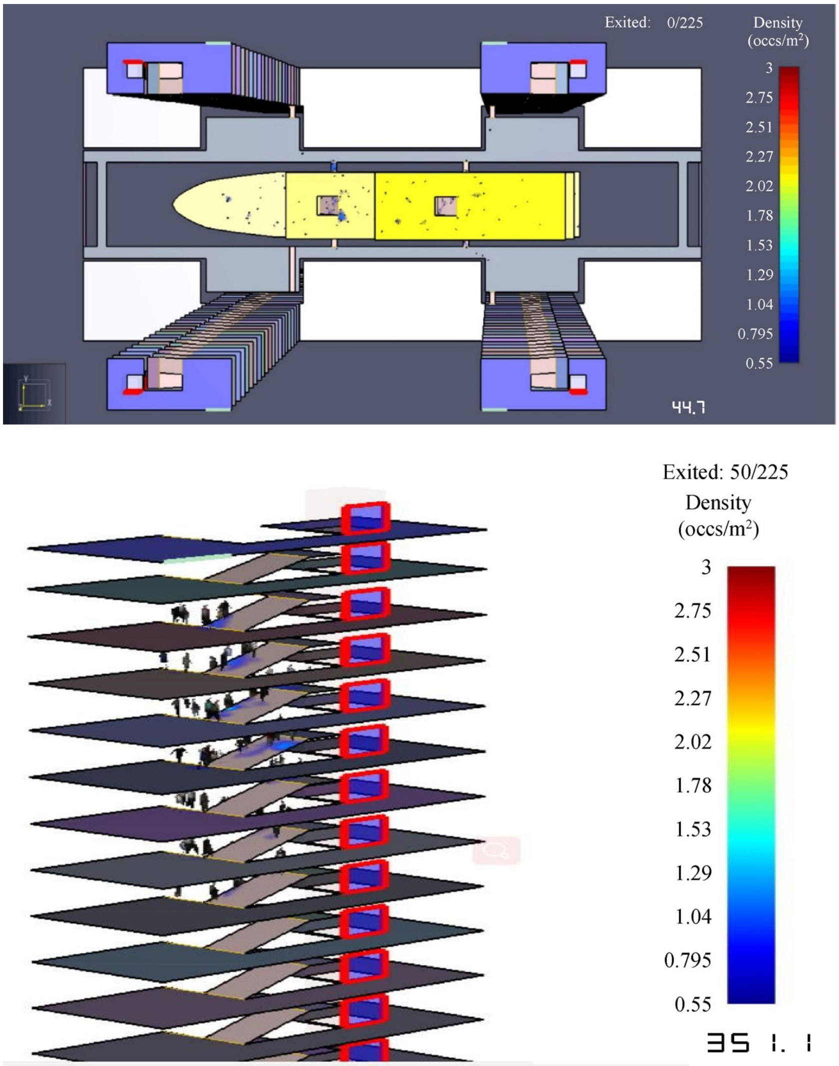

Fig. 6 Population density.

3.3 Elevator evacuation time

In the case of elevator evacuation, the elevator is assumed to run at full load at the maximum possible distance. Therefore, the elevator evacuation time is related to the number of elevator operations and a larger number of operations corresponds to a longer elevator evacuation time. Figure 8 presents the results of the three simulation cases.

The elevator evacuation time first reduces, subsequently increases, and finally reduces with the increase in the parking elevation when α is fixed. The evacuation time increases significantly with the increase in the use proportion of stairs when the number of evacuees is fixed. The elevator evacuation time reduces with the decrease in the number of evacuees when the use proportion of stairs remains unchanged; however, the reduction in the minimum evacuation time is smaller than the decrease in the maximum evacuation time.

3.4 Vertical evacuation time

The vertical evacuation can be investigated after analyzing the staircase and elevator evacuation procedures. The results are demonstrated in Fig. 9.

The vertical evacuation time first reduces, subsequently increases, and finally reduces with the increase in the parking elevation when α is fixed. Similar to the trend of the elevator evacuation time illustrated in Fig. 8, a sharp and rapid decline process occurs when the vertical evacuation time reaches the maximum value. Figure 9 indicates that the vertical evacuation time reduces as the number of evacuees decreases. The minimum and maximum evacuation times obtained when the number of evacuees is 225 and 125 occur at the elevation of 83 and 144 m, respectively, while the minimum and maximum times occur at 85 and 136 m, respectively, when the number of evacuees is equal to 50.

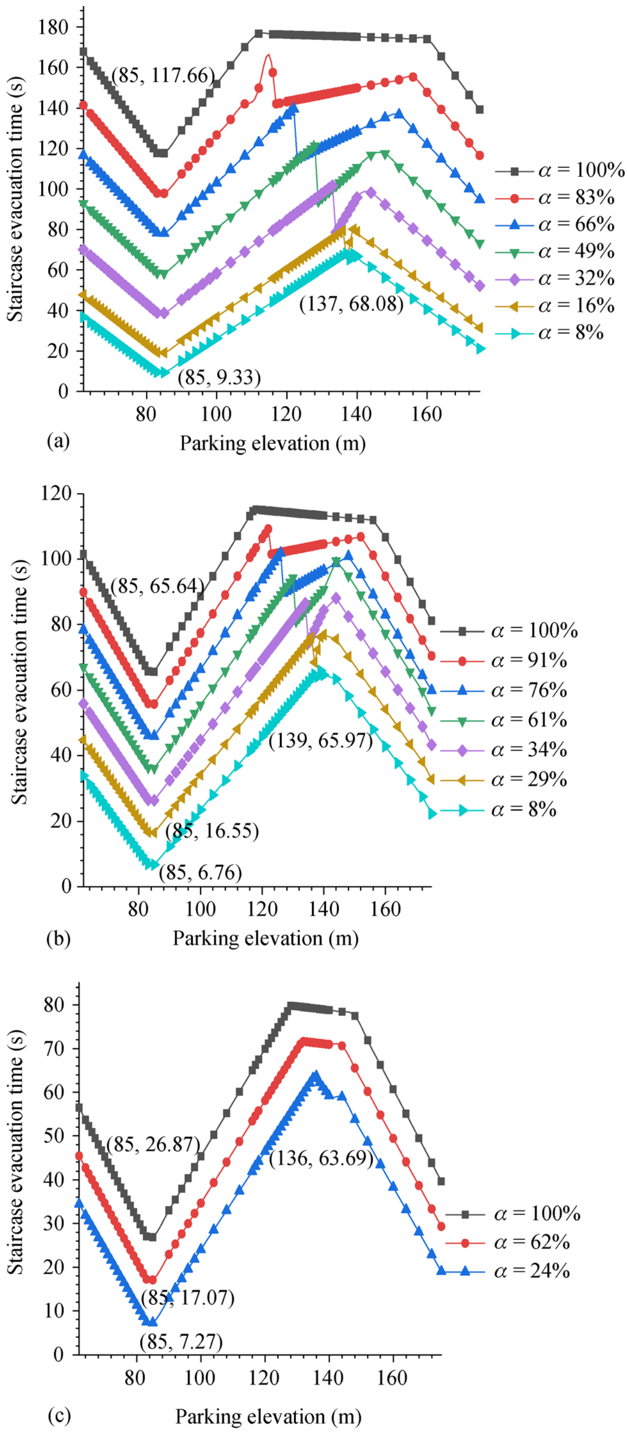

Fig. 7 Staircase evacuation time (the number of evacuee is set as (a) 225, (b) 125 and (c) 50).

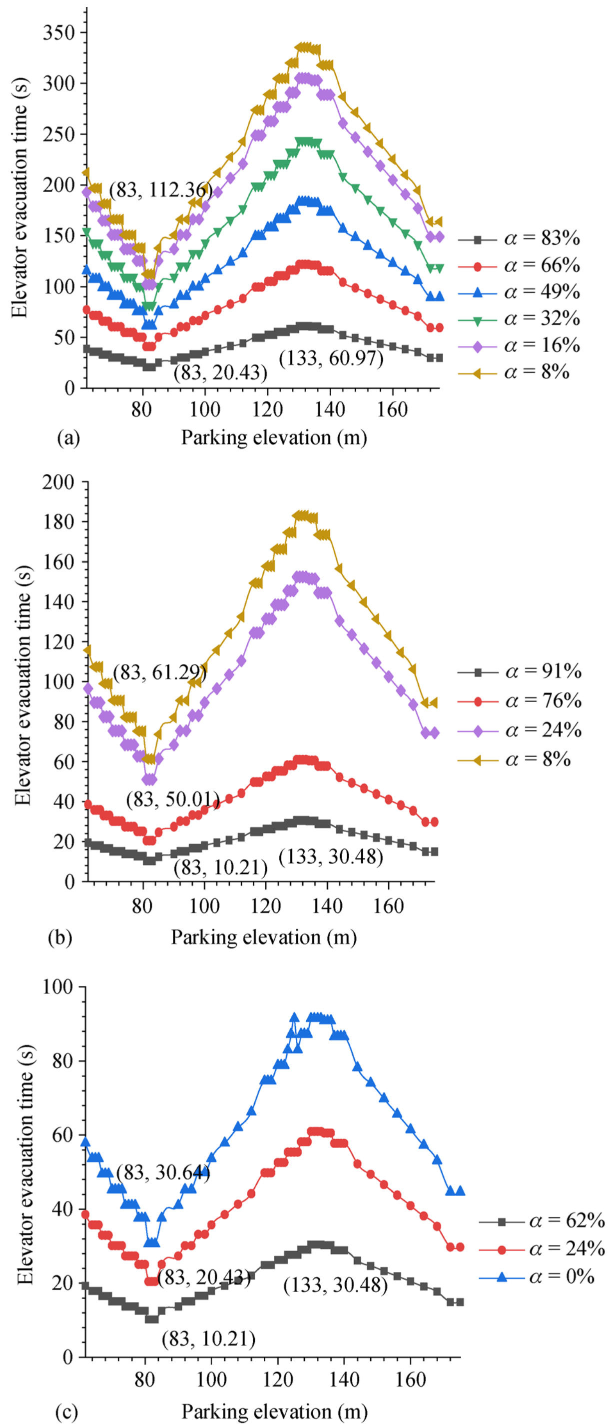

Fig. 8 Elevator evacuation time (the number of evacuee is set as (a) 225, (b) 125 and (c) 50).

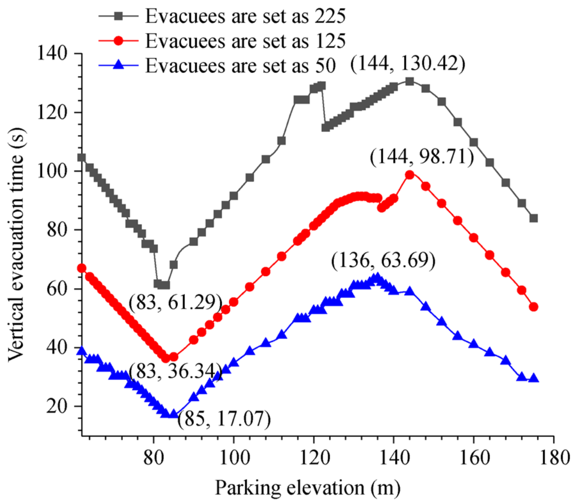

Fig. 9 Vertical evacuation time.

3.5 Analysis of factors influencing the vertical evacuation

The above simulation results demonstrate that the number of evacuees and the choice of the evacuation exit are important factors affecting the evacuation time. The relationship among different variables can be obtained subsequently and are analyzed as follows.

3.5.1 Influence of number of evacuees

Figure 10 presents the relationship between the vertical evacuation time and relevant proportions when the number of evacuees in the simulation is set as 225, 125, and 50, respectively.

The comparison of the three cases shows that the vertical evacuation time reduces with the decrease in the number of evacuees. The use proportion of stairs increases in the situation with dense crowds when the docking position is near the exit. However, the parking position of ship reception chamber near the evacuation exit corresponds to a high use proportion of stairs when the number of evacuees is small. In case 1, the optimal evacuation time is 61.29 s at 83 m with a corresponding α of 49% and the use proportion of stairs is reduced when the parking position is near the evacuation exit. In case 2, the optimal time is 36.85 s at 85 m with an optimal α of 54%. In case 3, the optimal time is 17.07 s at 85 m with an α value of 62%. Moreover, additional people opt to use stairs for evacuation when the parking position is near the evacuation exit.

3.5.2 Influence of exit selection

Selecting the appropriate exit for evacuation is an important factor affecting the evacuation time, and the choice of evacuation exit involves the direction of

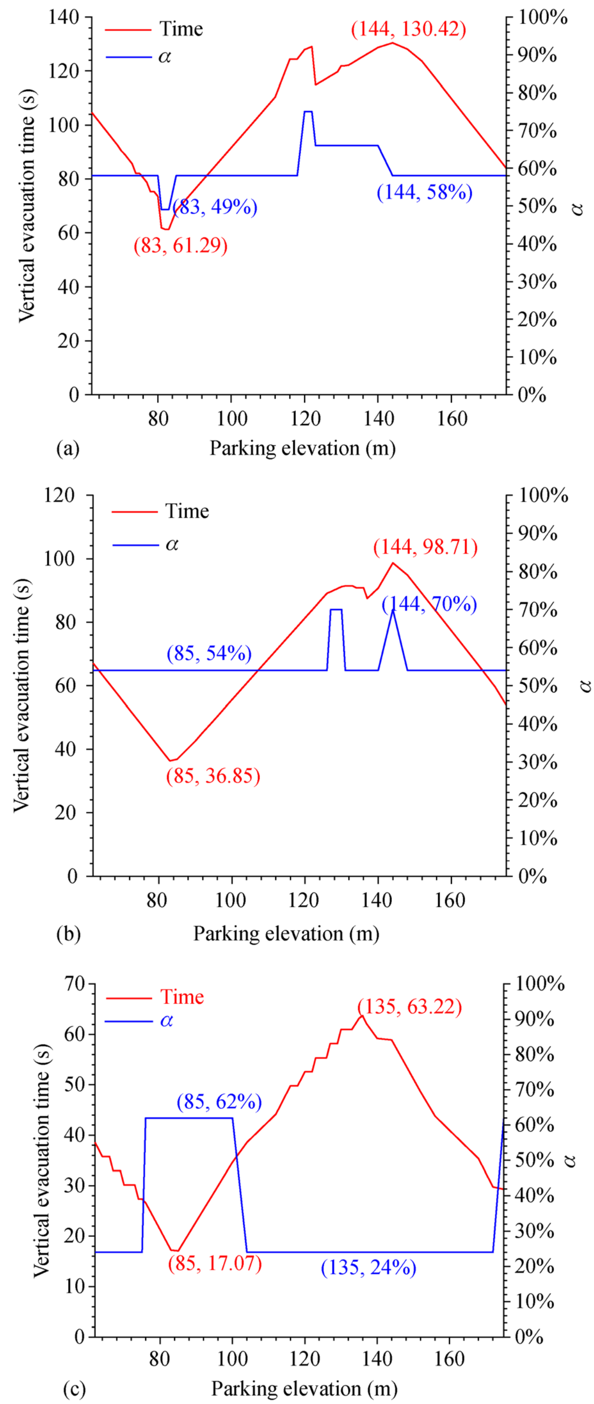

Fig. 10 Relationship among the number of evacuees, vertical evacuation time and ratio α (the number of evacuee is set as (a) 225, (b) 125 and (c) 50).

evacuation. The parking elevation of the ship reception chamber must be considered in the selection of the evacuation exit. A parking position near the evacuation exit theoretically facilitates the evacuation. The relationship among the parking elevation, evacuation time, and correlation proportion is illustrated in Fig. 11.

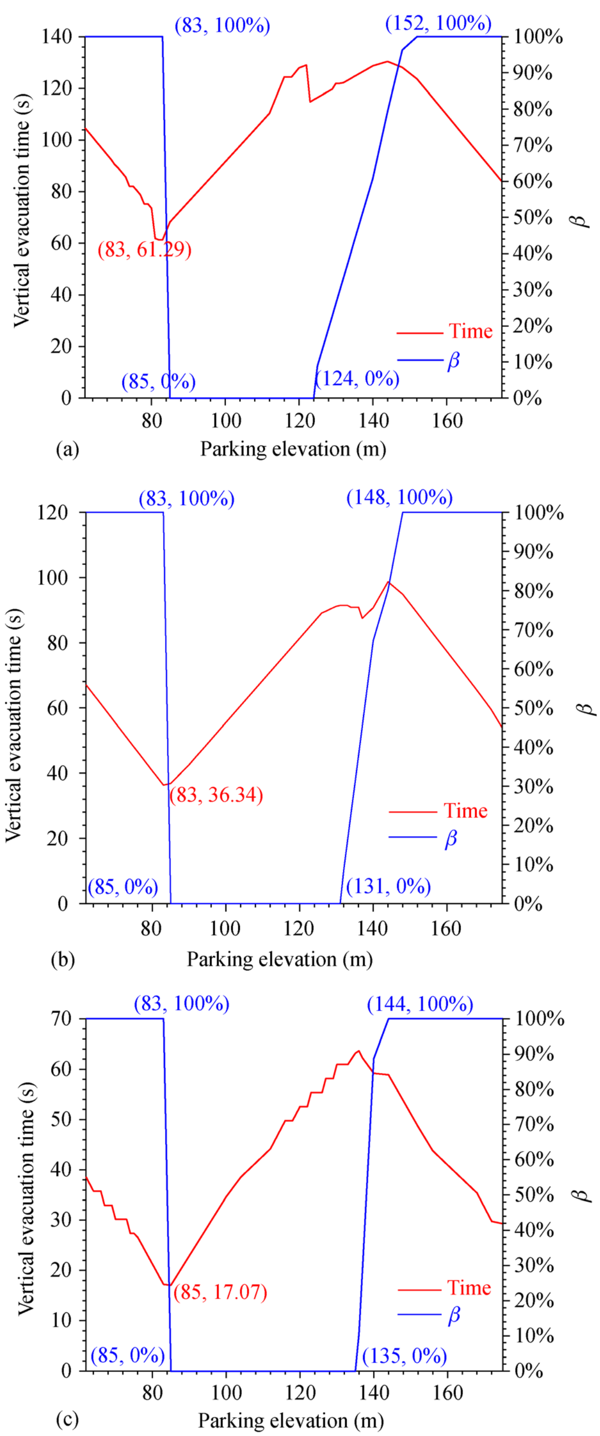

Fig. 11 Relationship among the parking elevation, evacuation time and ratio β (the number of evacuee is set as (a) 225, (b) 125 and (c) 50).

In case 1, the minimum evacuation time is 61.29 s, with 49% of the evacuees selecting staircases. The upward movement of evacuees to the downstream exit indicates that the optimal β value is equal to 100%. People opt to evacuate via the downstream exit when the parking elevation is $H \in [62, 84]$ or $H \in [152, 175]$. Evacuees must evacuate from the upstream exit when $H \in [85, 124]$. The changes in β with the parking elevation when $H \in [125, 151]$ indicate that people can opt to evacuate from two exits at the same time in this case.

In cases 2 and 3, people select downstream and upstream exits to evacuate when the ship reception chamber parks below 84 m or above 152 m, regardless of the number of evacuees. In these cases, people can evacuate via two exits at the same time in parking interval with a length of 15 and 7 m, respectively, when $H \in [132, 147]$. Therefore, the length of the parking interval reduces as the number of evacuees decreases.

4 Conclusions and future work

This article proposed an evacuation strategy that combines the use of elevators and stairs. A numerical simulation was performed considering the two parameters of number of evacuees and parking elevation that influence the minimum vertical evacuation time. The findings indicate that the comprehensive application of elevators and stairs can improve evacuation efficiency and provide guidance for the emergency evacuation of VSLs in the initial fire stage.

The results of considered cases show that the use proportion of stairs should be appropriately reduced in the case of a large number of evacuees when the parking position of the ship reception chamber is near the evacuation exit, to ensure the use of elevators for evacuation and minimize the total evacuation time. Additional people should evacuate using stairs when the number of evacuees is small and the berth position of the ship reception chamber is near the evacuation exit.

Regardless of the number of evacuees, occupants should select the downstream exit to evacuate when the ship reception chamber is parked below 84 m but leave via the upstream exit when the parking elevation is more than 152 m. Occupants can select to evacuate from both evacuation exits when the ship reception chamber is parked between 84 and 152 m. The primary influencing factor in selecting the exit is the distance between the person and each evacuation exit. The trend of the vertical evacuation time under the three working conditions is similar with the tendency of the elevator evacuation time. The nearly identical vertical and elevator evacuation times when the number of evacuees is small indicates that the elevator is the primary evacuation passage in this case.

Emergency situations are complex and dynamic, and factors, such as gender, age, fatigue, and social force of evacuees, may affect the fire evacuation process of VSLs. Thus, considering additional related factors in the analysis is a future research direction. A critical limitation of this research is the exclusion of the psychological state of evacuees as an influencing factor. Future investigations will focus on the influence of additional factors on the evacuation effect of VSLs and improve the integrated application of stairs and elevators.

References

Bao Y (2011). Study on fire prevention performance-based design of a large underground banquet hall. Applied Mechanics and Materials, 94–96: 2065–2069

Black W Z (2009). Smoke movement in elevator shafts during a high-rise structural fire. Fire Safety Journal, 44(2): 168–182

Butler K, Kuligowski E, Furman S, Peacock R (2017). Perspectives of occupants with mobility impairments on evacuation methods for use during fire emergencies. Fire Safety Journal, 91: 955–963

Cao Q, Huang L L, Xiao X K (2013). Study on the parameters of ultra-high-building evacuation by elevators. Fire Safety Science, 22(4): 207–212 (in Chinese)

Chen J J, Wang X G, Fang Z (2016). Collaborative evacuation strategy of ultra-tall towers among stairs and elevators. Procedia Engineering, 135: 170–174

Chen S, Shen H B, Wang Y, Wang J P, Li Z (2018). Strategy for emergency evacuation from vertical ship lift on initial fire. China Safety Science Journal, 28(2): 187–192 (in Chinese)

Chen S, Xi Y, Wang J P, Shang M H, Li Z (2019). Simulation optimization of evacuation schemes for vertical ship lift on initial fire. Journal of System Simulation, in press (in Chinese)

Ding N, Zhang H, Chen T (2017). Simulation-based optimization of emergency evacuation strategy in ultra-high-rise buildings. Natural Hazards, 89(3): 1167–1184

Ding Y C, Yang L Z (2013). Occupant evacuation process study of public buildings based on computer modeling and simulation. Journal of Applied Fire Science, 23(3): 365–380

Ding Y C, Yang L Z, Weng F L, Fu Z J, Rao P (2015). Investigation of combined stairs elevators evacuation strategies for high rise buildings based on simulation. Simulation Modelling Practice and Theory, 53: 60–73

Fang T, Yu J, Wang J (2012). Study of staircase design effects on evacuation in architectural plane design. Journal of Applied Fire Science, 22(1): 69–80

Fang Z, Lo S M, Lu J A (2003). On the relationship between crowd density and movement velocity. Fire Safety Journal, 38(3): 271–283

Fruin J J (1971a). Designing for pedestrians: A level-of-service concept. In: 50th Annual Meeting of the Highway Research Board. Washington DC, No. HS-011 999

Fruin J J (1971b). Pedestrian Planning and Design. New York: Metropolitan Association of Urban Designer and Environmental Planners

Graat E, Midden C, Bockholts P (1999). Complex evacuation; effects of motivation level and slope of stairs on emergency egress time in a sports stadium. Safety Science, 31(2): 127–141

Guo X M, Yao B, Li Z, Zuo T C (2018). Optimization study on high-rise building collaborative evacuation by combined use of stairs with elevators. Fire Safety Science, 27(1): 53–61 (in Chinese)

Hu C P, Yang Y (2007). A case study on fire evacuation by elevator in high-rise building. Journal of Natural Disasters, 16(4): 97–102 (in Chinese)

Huo F Z, Song W G, Chen L, Liu C, Liew K M (2016). Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building. Safety Science, 86: 165–173

Klote J H (1993). A method for calculation of elevator evacuation time. Journal of Fire Protection Engineering, 5(3): 83–95

Klote J H, Tamura G (1986). Elevator piston effect and the smoke problem. Fire Safety Journal, 11(3): 227–233

Kong D P, Lu S X, Ping P (2017). A risk-based method of deriving design fires for evacuation safety in buildings. Fire Technology, 53 (2): 771–791

Koo J, Kim Y S, Kim B I, Christensen K M (2013). A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation. Expert Systems with Applications, 40(2): 408–417

LaDue D, Tetreault B (2017). Improving navigation safety with better charts. Sea Technology, 58(3): 20–24

Lam W H K, Cheung C Y (2000). Pedestrian speed/flow relationships for walking facilities in Hong Kong. Journal of Transportation Engineering, 126(4): 343–349

Li J M, Hu C, Li Y F, Liu S S, Xu P (2014). Influence of crow density on the movement speed on different egress paths. Building Science, 30 (8): 122–129 (in Chinese)

Li X Y, Zhang K N, Ke Z J, Zheng D W, Lu F X (2018). Application research on firefighting system of ship lift chamber of Three Gorges. Fire Science & Technology, 37(7): 927–930 (in Chinese)

Lu S, Liu W S, Weng X, Li F Z (2012). Study on evacuation strategy in high-rise buildings fire. Advanced Materials Research, 472–475: 3207–3213

Ma J, Chen J, Liao Y J, Lo S M (2013). Efficiency analysis of elevator aided building evacuation using network model. Procedia Engineering, 52: 259–266

Ma J, Lo S M, Song W G (2012a). Cellular automaton modeling approach for optimum ultra-high-rise building evacuation design. Fire Safety Journal, 54: 57–66

Ma J, Song W G, Tian W, Lo S M, Liao G X (2012b). Experimental study on an ultra-high-rise building evacuation in China. Safety Science, 50(8): 1665–1674

NIST (2008). Changes to ICC building and fire codes—from FY 2008 NCST Annual Report. Available at: nist.gov/el

Pauls J (1987). Calculating evacuation times for tall buildings. Fire Safety Journal, 12(3): 213–236

Ronchi E, Nilsson D (2013). Fire evacuation in high-rise buildings: A review of human behaviour and modelling research. Fire Science Reviews, 2(1): 7

Sheehan R C, Gottschall J S (2012). At similar angles, slope walking has a greater fall risk than stair walking. Applied Ergonomics, 43(3): 473–478

Smith R A (1995). Density, velocity and flow relationships for closely packed crowds. Safety Science, 18(4): 321–327

Wang C, Wang H L, Han J Y (2014). The study of lift evacuation efficiency in super-high rise buildings. Fire Science & Technology, 33(11): 1257–1260 (in Chinese)

Wang J P, Wang M R, Zhang R X, Li Z (2018). Risk analysis of major hazard source of Three Gorges Ship Lift based on fuzzy theory. Yangtze River, 49(9): 98–102, 106 (in Chinese)

Wang J P, Wang M R, Zhou J L, Zuo Q J, Shi X X (2020). Simulation based optimal evacuation plan in vertical ship lift: A case study. Engineering Computations, 37(5): 1757–1786

Yang L J, Lu W B (2017). Introduction of the Three Gorges Ship Lift. Hydropower and New Energy, (1): 7–14 (in Chinese)