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Analysis of Human Competitive Behavior on an Inclined Ship

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Abstract: When a ship accident occurs, emergency evacuation of passengers in a shorter time is one of the most effective means of reducing casualties. However, in addition to the ship inclination, the efficiency of the emergency evacuation can be affected by human behaviour (*e.g.* competitive behaviour), which affects human moving speed. Therefore, to analyse the impact of competitive behaviour during ship evacuations, a dynamic evaluation system is developed to measure nested competitive behaviour. Firstly, the perceived area is obtained by dividing the pedestrian visual perspective, which is used to calculate crowd density at every time step. Secondly, fuzzy logic is used to calculate the real-time competitive degree based on the inclined angle and crowd density, integrated into the human evacuation model as an input parameter to update competitive behaviour. Finally, this study analyses and evaluates evacuation time and efficiency with different proportions of competitive people at different inclined angles, using a dining room on a ship as a case study. The results show that, without ship inclination, the total evacuation time decreases with the increase of the proportion of competitive people as more competitive people can speed up the evacuation process. While the inclination of a ship leads to a decrease in human walking speed, congestion at the exit, and a slower overall evacuation process. According to the

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findings of this study, an appropriate increase in the proportion of competitive human is beneficial to the efficiency of emergency evacuation. And strengthening the guidance at the exit will also reduce the evacuation time.

Key words: Maritime Safety; Competitive Behaviour; Emergency Evacuation; Social Force Model; Ship Inclination.

Introduction

In recent years, the cruise tourism market has been expanding in line with economic development. The increasing number of passengers and market demand lead to the large size of passenger ships, resulting in more safety issues. Particularly, once an accident occurs during the operation of a passenger ship, it often leads to serious casualties and property damage(Cao et al., 2023b; Huang et al., 2023a). Therefore, to improve the safety level of passenger ships, IMO has put forward a series of evacuation requirements for passenger ships. According to the requirements of MSC.1/Circ.1533, ships built after 1 January 2020 should be carried out the evacuation analysis (IMO, 2016). At the same time, to study the characteristic human movement parameters and evacuation efficiency during ship evacuation, some researchers have also conducted a series of experiments (Liu et al., 2022; Wang et al., 2021c; Wang et al., 2021d). Although theoretical analysis has been developed, for safety reasons, it is still unrealistic to carry out ship evacuation experiments in a real emergency. Therefore, the existing evacuation experiments will have biases with reality as they are carried out in non-emergency situations, which affects the validity of the results to a certain extent.

With the continuous development of computer modelling techniques, evacuation model simulation has highlighted the significant advantages (Fang et al., 2023). In existing studies, evacuation models are mainly classified into macro-models and micro-models based on the modelling scale, and have been studied in detail in large gathering places such as land buildings or stations (Haghani, 2020a, b). Macro-models mainly provide theoretical support for managers in the formulation of evacuation strategies and the calculation of available evacuation time, such as fluid-dynamic model (Wang and Jia, 2022). Micro-models primarily concentrate on characterizing individual attributes and the interactive behaviours between individuals and their environments. These models offer a chance for studying complex evacuation systems, with cellular automata and the social force model being particularly popular choices (Ntzeremes et al., 2020). Notably, the social force model, as a representative continuous simulation model, has been used in various commercial evacuation software. This means that, through the secondary development of existing evacuation software, the continually refined social force model can be employed in more complex and extensive evacuation scenarios, achieve a wider range of applications. Given these advantages, the social force model is selected as the evacuation model for this study, with the intention of facilitating comprehensive human evacuation analysis on ships in future research endeavours.

However, compared with the mature field of land-based evacuation, the human evacuation onboard ships required the consideration of many specific factors, such as the assembly station, the type of ship accident and the life-saving equipment, etc. These influencing factors not only put forward new requirements for evacuation modelling but also lead to a wide range of heterogeneous behaviours during the evacuation process (Arshad et al., 2022; Cao et al., 2023a; Wang et al., 2022). While heterogeneous behaviours have garnered growing attention from researchers, and certain studies have highlighted their potential to either facilitate or impede overall evacuation processes, less attention has been directed towards investigating the impact of such heterogeneous behaviours on shipboard evacuations. The questionnaire surveys have revealed that owing to the complex layout of ships and the unique evacuation procedures involving lifeboat embarkation or other life-saving equipment, a significant portion of passengers admit to experiencing nervousness, fear, and other emotions. It is confirmed that the likelihood of heterogeneous behaviours occurring during ship evacuations is heightened at a psychological level (Galán, 2021; Huang et al., 2023b; Wang et al., 2021a; Wang et al., 2023; Wang et al., 2021e). In addition, existing research has shown that human often exhibit competitive behaviours during shipboard evacuations, especially in emergencies, where they are more likely to engage in typical competitive behaviours such as overtaking, pushing, and running(Wang et al., 2020). For example, by investigating the Costa Concordia accident, Bartolucci found that people always showed more competitive behaviour when boarding lifeboats, and that as the ship tilted more and more due to water ingress, more and more people showed 'panicky' behaviours (Bartolucci et al., 2021). The above studies have analysed the human competitive behaviour from the perspective of psychology or sociology, while most studies still lack the detailed information in the modelling and implementation process, which leads to a gap between the model and the underlying theory.

To fill the gaps in the current research, it is necessary to determine the human competitive behaviour in conjunction with the type of ship accident or the severity of the accident when building an evacuation onboard ships model, which is able to analyse more accurately the impact of human behaviour factors during the evacuation process. Therefore, this study aims to analyse the evacuation efficiency in different scenarios by building a human evacuation onboard ships model specifically designed for onboard ships. This model incorporates a dynamic assessment system to account for nested competitive behaviour, particularly in the context of ship water ingress accidents. Based on the ship inclined angle and the crowd density in the individual's perception area, the improved model uses a fuzzy system to calculate the real-time competition level of competing passengers. This calculation is then integrated into the evacuation model as an input parameter to update and simulate the competitive behaviours of people during evacuations.

Related works

Evacuation on inclined ships

The high tendency of ships to exhibit an inclined attitude after an accident at sea, as in the case of the "Costa Concoria" and "Sewol", means that the effects of ship inclination on human movement must be taken into account when studying the evacuation onboard ships(Wang et al., 2021b). When evacuating an inclined ship, human need to adjust their body state in order to maintain normal walking, while this adjustment is at the expense of speed. To measure the walking speed in inclined ships, the researchers have carried out a series of experiments on the human walking.

Researchers at the Research Institute of Maritime Engineering and the National Maritime Research Institute of Japan tested human movement parameters when the ship was inclined in a combination of corridor simulators and real ship experiments. They found that not only human walking speed decrease when the ship was inclined, but human also wanted to keep a distance from each other more than when the ship was floating on even keel (Murayama et al., 2000). The researchers of the Australian

Maritime Engineering Cooperative Research Centre found that in the case of small inclination, the human speed going downhill along the incline direction increased with the increase of the inclined angle, while the influence of heeling and uphill on the speed was not significant. But when two people walk side by side, their speed is lower than when they walk alone (Brumley and Koss, 1998). Researchers at the Netherlands Organization for Applied Scientific Research organised experiments in a ship motion simulator and found that the slope had a greater effect on human speed when facing uphill than downhill, but that handrails were effective in helping to walk (Bles et al., 2001). In contrast, researchers at the Korea Research Institute of Ships and Ocean Engineering did not agree with this conclusion. After conducting experiments using a corridor simulator, due to psychological factors and the angle of incline, they found that the human speed decreased rather than increased when traveling downhill (Lee et al., 2004). In addition, Sun et al. (2018) built a two-degree-of-freedom inclined ship corridor simulator. They concluded that when the inclined angle was less than 10°, human would be affected by gravity resulting in an increase in walking speed. Compared to trimming angle, the same heeling angle had the least effect on human speeds.

Since there is no clear standard for the experimental scenarios and experimental conditions, and the exercise ability of the participants in the experiment is quite different. As a result, the conclusions drawn from the above experiments are also quite different. At this stage, to enrich the results of the evacuation experiments, some human movement models in inclined ships have been proposed. In these studies, evacuation models are mainly used to carry out continuity calculation, so as to more systematically show the influence of the inclination effect on the human movement. By improving the common evacuation model, Kang et al. (2019) improved the basic social force model based on pedestrian dynamics, and analysed the influence of ship inclination on human walking in different moving directions. Fang et al. (2022) developed a human evacuation model in terms of reanalysing the force applied to human in the inclined ship, and applying it to the full-size evacuation simulation. The Hamburg Ship Model Basin Newsletter in Germany submitted a report to IMO containing an estimated function of the human speed at different inclined angles, which also considered the variability of human walking on corridors and staircases (Valanto, 2006). Kim et al. (2019) developed a simulation model for the disaster of the “Sewol” by focusing on the analysis of the human density and the congested area. This study compared the change of the evacuees in the evacuation simulation and real accident as well as predicted the casualties.

Competitive behaviour during evacuation

During land-based personnel evacuation, real evacuation videos and experimental footage have documented the human competitive behaviour. Many studies have focused on the impact of human competitive behaviours on evacuation efficiency. Cao et al. (2021) simulated the human evacuation from exits of different sizes considering human competitive and cooperative behaviours, respectively. Moreover, the arching phenomenon was observed as crowd gathered at the exit. von Schantz and Ehtamo (2019) redefined the human local decision-making model using a spatial game approach and elaborated on the cause of the arching phenomenon at bottlenecks. They found that the competition led to an increase in the internal force of the crowd, which makes it prone to accidents of falling and stepping accidents. Hidalgo et al. (2017) proposed an elliptical human shape based on real experiments, and the accuracy of the simulation model was improved by adding rotation movements. Meanwhile, they proposed a strategy to reduce the congestion time at the exit. Zheng and Cheng (2011) proposed a model including human cooperation and competition behaviour based on game theory. Their results showed that human competitive behaviour was related to the degree of urgency during evacuation and too low competition ratios would reduce the evacuation efficiency. Gao et al. (2016) modified the exclusionary force of corners on human to reflect the human competition degree through collision avoidance behaviour. Comparing the experimental results, the improved model was verified to be able to effectively predict the human collision avoidance behaviour at different competitive levels.

However, due to the special marine operating environment and limited evacuation space, it is difficult to obtain real video footage from the accidents for studies on the human evacuation onboard ships. To fill this gap, Kvamme (2017) analysed the “Costa Concordia” accident report in detail and found that a higher number of competitive behaviours increased the likelihood of secondary disasters. This study argued that it was necessary to consider human behaviours in ship evacuation models. Bartolucci et al. (2021) interviewed survivors of the accident and counted the probability of heterogeneous behaviours in different locations and at different moments. The results showed that competitive behaviours were likely to appear in special space, especially when boarding lifeboats, which was admitted by the majority of the people. By comparing the effects of different proportions of competitive people on evacuation efficiency, Kang et al. (2019) found that the inclusion of a small number of competitive human could reduce evacuation time, while too large proportion may show a negative impact on evacuation efficiency. Wang et al. (2020) surveyed 1380 passengers, 44% of the participants said that they were likely or very likely to have competitive behaviour. Especially in emergency situations, passengers would more tend to complete evacuation quickly. However, when people did not feel the existence of danger, they would have a higher proportion of solidarity and cooperation in the evacuation process.

Research gaps and contributions

An extensive literature review found that there is still a gap in evacuation models that take into account the human competitive behaviours. Although, some studies have attempted to analyse human behaviours during human evacuation onboard ships through simulation models, most of them referred to results of land-based human evacuation, which does not connect ship accidents with competitive behaviour. Moreover, these studies often categorize individuals as either exhibiting competitive behaviours or not, using an all-or-nothing approach that fails to capture the nuanced evolution of competitiveness throughout the entire evacuation process. In reality, the level of human competitiveness continuously fluctuates in response to environmental factors during an evacuation. Therefore, it becomes imperative to assess competitiveness dynamically in real-time, taking into account the emergency severity of the evacuation (accident severity) and crowd density when simulating human competitive behaviours. This dynamic approach is essential for ensuring that simulation results closely align with real-world scenarios. Based on this, to fill the existing research gap, this study proposes a ship evacuation model with a nested human competitive degree assessment system and analyses the human evacuation results of different inclined angles by simulating the evacuation scenario of a single-exit room. The contribution of this study is:

a) The competitive degree is introduced into the evacuation model by improving a real-time assessment system of human competitive desires. Using fuzzy system theory calculates the competitive degree in each time step based on the inclined angles and the density in the perceived area of the competitive people.

b) By dividing the pedestrian visual perspective, the area within the competitive people perspective and a small blind area are set as the perceived area. The competitive people calculate the crowd density at every time step according to the number of people counted in the perception area. This redefined pedestrian perspective can more closely describe the impact of people around them on competitive people.

c) By setting different inclination angles, the evacuation performance of different competitive degree is analysed and evaluated. Common evacuation phenomena can be effectively observed, and more importantly, counting the time interval between two consecutive people passing through the exit can help us better understand the evacuation process from the qualitative aspect.

Methodology

In this study, the simulation process is primarily comprised of three key components: the dynamic assessment system for evaluating human competitiveness, an evacuation model designed for human evacuations on inclined ships, and the resultant data, as illustrated in Fig. 1. At the outset of the simulation, a fuzzy system is employed to calculate the degree of human competition, taking into account factors such as the number of competitive individuals and the degree of ship inclination. These calculated results are then used as parameters within an enhanced social force model. Subsequently, the simulation outcomes are generated through interactions involving collision avoidance and competitive behaviours among individuals within the crowd. These interactions serve to continually update the evacuation status and the locations of the individuals involved.

Social force model for inclined ship

The social force model is a popular microscopic evacuation model that is known for its reliability and compatibility. It is widely used to predict and optimize crowd evacuation during emergencies and disasters, with the goal of improving the safety and survival rate of individuals. The social force model is a unique combination of psychological aspects of pedestrian movement and Newtonian mechanics. It is initially introduced by Helbing for the purpose of evacuation modelling and has been widely used to explain pedestrian self-organization phenomena, including the bottleneck effect and "fast is slow". The model has been further improved to cater to the study of crowd dynamics in various contexts (Helbing and Molnar, 1995). The social force model is primarily based on the physical forces and psychological changes of individuals. It takes into account factors such as the self-driven force generated by the attraction of the target exit, pedestrian-pedestrian and pedestrian-boundary forces, and random forces. By using parameter settings, the model prompts pedestrians to move with the combined force of these physical and psychological forces. The direction of pedestrians' movement is not restricted, allowing for slight overlapping between pedestrians due to overcrowding, which is a common occurrence in real-life emergency situations. The social force model expresses crowd dynamics as shown in Eq. (1).

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \boldsymbol{f}_{will} + \sum_{j(j \neq i)} \boldsymbol{f}_{ij} + \sum_{W} \boldsymbol{f}_{iW} + \xi \tag{1}$$

where, m_i represents the mass of pedestrian i, $\boldsymbol{v}_i$ is the real-time speed of pedestrian i, and t is adjustment time. $\boldsymbol{f}_{will}$ is the desired force, which represents the attraction effect of the target on the pedestrian's moving direction; $\boldsymbol{f}_{ij}$ and $\boldsymbol{f}_{iW}$ represent the interaction between other pedestrians j and obstacles or walls and pedestrian i, respectively, which is mainly to achieve collision avoidance between pedestrians and between pedestrians and obstacles. ξ is the random force.

The dynamics of pedestrian evacuation in an inclined ship have been fully discussed in previous studies. Compared to walking on flat terrain, pedestrians are affected by the ship inclined force $\boldsymbol{f}_b$, and this force always point from the high terrain to the low terrain. At the same time, to overcome negative effect of the inclined ship on walking, human may take actions such as grasping the railings and adjusting their body weight in the inclined scenario. In the force model, such actions are realized by the self-adjustment force $\boldsymbol{f}_{adj}$ (Fang et al., 2022; Jiang et al., 2022). Therefore, the pedestrian movement in the inclined ship space is shown in Eq (2):

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \boldsymbol{f}_{will} + \sum_{j(j \neq i)} \boldsymbol{f}_{ij} + \sum_{W} \boldsymbol{f}_{iW} + \boldsymbol{f}_b + \boldsymbol{f}_{adj} + \boldsymbol{\xi} \tag{2}$$

Competitive behaviour

Most existing studies on human competitive behaviour often revolve around the concept of individuals seizing target points, particularly in discrete models like the cellular automata model. These models offer a simpler way to describe competitive and cooperative behaviours. However, one limitation is that in the cellular automata model, the movement directions of individuals tend to be relatively fixed. This can result in competitive individuals failing to secure their desired positions during the simulation.

In contrast, the social force model characterizes human movement through force, without the direct setting of specific human movement parameters. This means that the social force model relies on fewer variables, resulting in more robust simulation outcomes. Although the task of seizing target points can be achieved in force-based models by extrapolating future time steps, this approach transforms the social force model from a continuous model into a discrete one. This transformation is less than ideal as it significantly increases the computational demands of the model and causes it to lose some of the crowd aggregation characteristics that are preserved in the continuous model. In fact, competitive behaviour expresses the desire of people to reach the goal point faster, which means that the desired speed of competitive people increases continuously with their competitive degree (Cao et al., 2021; Sticco et al., 2022; von Schantz and Ehtamo, 2019). Eq. (3) explains the calculation of desired force in the base social force model.

$$\boldsymbol{f}_{will}=m_i\frac{v_i^0(t)\boldsymbol{e}_i^0-\boldsymbol{v}_i(t)}{\tau} \tag{3}$$

where, $v_i^0(t)$ is the desired velocity of the pedestrian i, $\boldsymbol{e}_i^0$ is the target direction of the pedestrian, $\boldsymbol{v}_i(t)$ is the real-time speed of the pedestrian i at moment t, and τ is the reaction time. The desired force is the main driving force for the human movement, which is driven by the mode that the human needs to adjust the magnitude and direction of his/her real-time velocity to the desired velocity and desired direction as much as possible within the reaction time.

Extensive research has found that the emergence of competitive behaviours among people is largely dependent on the surrounding environment. Especially, when there is little escape time available, the likelihood of exhibiting competitive behaviours and the desire to compete is greater in a crowd (von Schantz and Ehtamo, 2019). In addition, the density of surrounding people can also have an impact on human competitive psychology. Close proximity and slow movement speeds between individuals in congestion areas can lead to the emergence of more competitive behaviours. (Sun and Liu, 2021). However, the human competitive behaviour is not influenced by all the people around them but is determined by the density in the perceived area. According to (Fang et al., 2021), the competitive people field of view angle is set to 120° and the radius of the field of view is 2 m in this study. Meanwhile, the range of 0.5 m within the blind spot of the view field is also set to be the perceived area because human who are nearer at the rear can be sensed through sound and other means in real life. As shown in Fig. 2, human need to be screened to determine the number of potentially affected pedestrians when calculating the density of people around them. The light-colored area in Fig. 2 is the perceived area of the pedestrians, and the dark-colored area is the blind area of their field of view.

Due to the rapidly changing situation during the evacuation process, the level of competition among people is also uncertain at any given moment. A quantitative value is used in previous studies to constant whether human have competitive behaviours or the competitive degree (Lin et al., 2019), while this method is inaccurate in the actual evacuation process. Therefore, this study proposes a fuzzy system based on the inclined angles and the density of people to calculate the competitive degree at each moment, as shown in Fig. 3. A fuzzy inference system is a collection of fuzzy sets, fuzzy affiliation functions, and fuzzy rules used to simulate the decision-making process, including three phases of fuzzification, inference, and defuzzification (Yang et al., 2020). The fuzzification stage converts the input values of clear inclined angle and density into fuzzy affiliation values by means of fuzzy sets and fuzzy affiliation functions. Based on the database and rule base, the defuzzified inputs are used to calculate the defuzzified outputs using decision units in the inference stage. Finally, in the defuzzification stage, the fuzzy sets and fuzzy affiliation values of the output variables are converted into clear values. In this system, the Mandani inference method is used to construct the fuzzy implication relation by the Cartesian product of fuzzy sets. The defuzzification process is calculated using the Centroid method, which involves determining the centre of gravity of the area bound by the output affiliation curve and the horizontal axis. This value is then used as the output value of the fuzzy inference system to adapt to small input signal variations.

The expressions of fuzzy rules and fuzzy implications are shown in Eqs. (4) and (5):

$$R_i = (A_i \ and \ B_i) \rightarrow C_i \tag{4}$$

$$\mu_{Ri} = [\mu_{Ai}(x) \text{ and } \mu_{Bi}(y)] \rightarrow \mu_{Ci}(z) \tag{5}$$

where A_i denotes the fuzzy set of inclined angles, B_i denotes the fuzzy set of density, C_i denotes the fuzzy set of competitive degree, R_i is the fuzzy relationship matrix. μ is the affiliation of the input and output parameters. x, y, and z denote the semantics of the inputs and outputs correspondingly.

In the input, the fuzzy variable A_i for inclined angle has three linguistic values (S-small, M-medium, L-large); the fuzzy variable B_i for density also has three linguistic values (L-low, M-medium, H-high); and the competitive degree C_i has five linguistic values (VS-very strong, S-strong, M-moderate, W-weak, and VW-very weak). Based on the design principle of fuzzy rules and the experience of observing human competitive behaviours, people tend to quickly leave the current area when the angle of inclination is very steep or the density of people in their field of view is high. This behaviour helps to avoid further congestion or severe overcrowding caused by the congregation of people or seriousness of inclination. The fuzzy set of input variables can be listed as 3×3=9 rules, and the detailed rules for assessing the competitive degree are shown in Table 1. Taking the first rule as an example, if the inclined angle belongs to the set "Small" and the density belongs to the set "Low", then the competition degree belongs to "Very Weak". In addition, Fig. 4 displays the logical operations of the fuzzy rule. The yellow area represents the input inclined angle and density parameters' affiliation to each set, and the blue area shows the output competitive degree's affiliation to each set. To perform mathematical operations in the evacuation model, it's necessary to convert the competitive degree into numerical values through defuzzification. Fig. 5 illustrates the competitive degree of people in various situations. As observed, the competitive degree increases with an increase in the inclined angle and density of people in the perceived area.

The results of the calculations mentioned above indicate the need to update the desired speed of competitive individuals in real-time, based on their competitive degree in the model. The expression of the social force model shows that the desired speed of competitive people usually increases exponentially with an increase in their competitive degree, as depicted in Fig. 6 (Cao et al., 2021). In this study, the normal desired velocity $v_i^0(t)$ is set to 1.3 m/s, and the desired velocity of the competitive people is calculated by Eq. (6):

$$v_c^{0}(t) = v_i^{0}(t)\left\{1 + exp[\mathrm{m}\chi_i(t) - \mathrm{n}]\right\} \tag{6}$$

where, $v_c^0(t)$ is the desired velocity of the competitive people, $\chi_i(t)$ is the competitive degree of pedestrian i in the moment t. m and n are constants.

Fig. 7 provides a brief overview of the model execution and the human movement procedure. The model determines whether individuals exhibit competitive behaviour or not based on the input the proportion of competitive people. At each time step, individuals with competitive behaviour are required to identify potentially influential crowds around them and update their degree of competitiveness and desired speed accordingly. The evacuation model then updates and stores the positions and speeds of all evacuees by calculating the combined forces until everyone has been evacuated.

Simulation results and discussion

Case scenarios setting

The dining room of a ship is chosen as the evacuation scenario in this study, which is a square with a side length of 15 m and a exit width of 1 m. Due to the limited space of the ship, this room also serves as a recreational facility for passengers, a large number of people gather for an extended period. Therefore, this room is selected to highlight the effect of inclined ships on human movement and effectively characterize onboard ship evacuations, particularly the heterogeneous behaviour of competitive people. Fig. 8 illustrates the initial distribution of people in the model, where the initial assumptions of the proportion of competitive people α is 0.5. The red circles represent competitive people, the blue circles represent normal individuals, and the size of the circles represents different individuals' size. It's worth noting that parameters such as radius, mass, positions, and desired speeds of different individuals are randomly distributed. To avoid chance in a single experiment, the simulation is repeated 100 times for each case in this study.

Effects of different competitive degree on evacuation

Fig. 9 presents the results of 100 simulations with varying proportions of competitive people when the inclined angle θ is 0°. The simulations demonstrate strong robustness and an even distribution of results. Comparing the average evacuation time for each scenario, it can be concluded that competitive people have a positive effect on total evacuation time. As the proportion of competitive people increases, the total evacuation time tends to decrease. This finding is consistent with the previous study (Cao et al., 2021). However, in this study, the competitive degree is determined by two factors: the inclined angle and the crowd density in the perception area. As a result, the competitive degree is small when $\theta = 0°$, leading to a relatively slow trend in the total evacuation time in Fig. 9 with no significant difference.

Fig. 10 shows that the evacuation paths of different proportions of competitive people tend to be curved and jittery near the exit. This is mainly due to congestion caused by a large number of people gathering at the exit after the evacuation has started. Even though competitive people have a higher desired speed at this point, congestion still restricts the overall evacuation process. In contrast to von Schantz and Ehtamo (2019), this study did not observe significant stratification between competitive and normal people. This is because at the beginning of the evacuation phase, people are more dispersed, resulting in a lower degree of competition among competitive people and similar evacuation trajectories between competitive and normal people. However, as a large number of people gather at the exit, both competitive and normal people are subject to greater congestion, resulting in greater inter-crowd forces and desired forces for all pedestrians. At this point, all individuals have an urgent desire to evacuate from the room, making it impossible to observe a clear stratification phenomenon.

In Fig. 11, this model is compared to study (von Schantz and Ehtamo, 2019) of flow rates at exits. The results show that von Schantz's study reaches its maximum at a competitive proportion of 0.25, while this model reaches its maximum at a competitive proportion of 0.5. This difference is primarily due to the fact that the competitive behaviour identified in this model changes in real-time, resulting in a delayed and varying degree of competition, which is more in line with reality where individuals cannot always remain competitive. Additionally, the exit width in this paper is 1m compared to von Schantz's exit width of 1.2m, resulting in a lower overall exit flow rate. However, when comparing Fig. 9, it can be seen that although the flow rate at the exit reaches its maximum at a competitive proportion of 0.5, the total evacuation time is still the smallest at a competitive proportion of 0.9. This may be because Fig. 11 calculates the average flow rate at the exit, and when the proportion of competitive people is 0.5, although the escape speed of this part of the crowd increases, the arch formed at the exit lasts for a longer period of time, resulting in an increase in the exit flow rate without reducing the total evacuation time (Sticco et al., 2022).

In order to describe the evacuation process at the exit in more detail, Fig. 12 plots the empirical survival function of pedestrians in log-log axes. The statistic is the probability that the time interval ΔT between two consecutive people passing through an exit is greater than δt. In Fig. 12, when a point's x-coordinate is 10^0 and its y-coordinate is 10^{-1}, it indicates that the probability of the time difference between two consecutive people passing through the exit exceeding 10^0 s is 10^{-1}. Furthermore, the probability of ΔT being greater than 0.1 s is 1 for all three scenarios with $\alpha = 0.1, 0.5$, and 0.9, as shown in Fig. 12, this suggesting that in all of these scenarios, the ΔT is greater than 0.1 s. It is noteworthy that in this model, an increase in the proportion of competitive people tends to reduce the likelihood of longer ΔT intervals. However, the opposite phenomenon is observed in the study (Hidalgo et al., 2017), i.e., increasing the desired speed leads to longer congestion, this is due to the incorporation of a real-time system for assessing the competitive degree in this model. The competitive degree depends on density in the perception area, but the competitive people may not always remain in a fully competitive state. And, with the density of people in the perception area increasing, the desired speed of competitive people increases, and thus a longer ΔT is less likely to occur, which is why the "fast is slow" phenomenon does not occur (Garcimartín et al., 2016). However, it is worth noting that the probability of simulations obtaining $\Delta T > \delta t$ remains of the same order of magnitude as the results of real experiments (Feliciani et al., 2020; Hidalgo et al., 2017).

Effects of competitiveness on different inclination angle

In the event of a ship's inclination due to water ingress, passengers on board can quickly perceive that they are in an uneven space, which can cause panic to those inside the cabins. Panic tends to intensify as the inclined angle increases (Wang et al., 2020). Fig. 13 illustrates the total evacuation time when the proportion of competitive people increases from 0.1 to 0.9 in different inclination scenarios. It can be observed that when the ship is inclined at a certain angle, the total evacuation time tends to decrease as the proportion of competitive people increases. When $\theta = 25°$, the total evacuation time decreases by 38.44s when the proportion of competitive people increases from 0.1 to 0.9, while it only decreases by 16.02s when there is no inclination. It is worth noting that although there is a significant difference in the reduction of total evacuation time, the reduction is stable in the range of 18.45%-22.71% in corresponding scenarios. Additionally, when $\theta \leq 10°$, the total evacuation time decreases the fastest when α is 0.5. The reason for this is that the flow rate at the exit reaches its maximum at this point, effectively improving overall evacuation efficiency, which is consistent with results obtained in Fig. 11. However, when $\theta > 10°$, the evacuation time decreases the fastest at $\alpha = 0.7$ due to the reduction in movement speed of all individuals caused by the large inclined angle, and at this point, the exit flow rate does not reach its maximum at $\alpha = 0.5$. Therefore, compared with scenarios on flat ground or small angles of inclination, increasing the proportion of competitive people can effectively promote overall evacuation efficiency and process in appropriate situations.

Similar to the description above, the survival function of people can visualize the efficiency of different evacuation scenarios. Fig. 14 illustrates the exponential distribution of the probability of $\Delta T > \delta t$ for different inclination angles for $\alpha = 0.5$, which displays congestion at the exits in various scenarios. Higher congestion resulting in a higher probability that ΔT becomes longer indicates that congestion at the exits lasts for a longer period of time (Fang et al., 2022). It is worth noting that when the survival function at $\theta = 25°$ is further away from the other two curves, which means that the greater the amount of attenuation of walking speed, the longer the duration of crowd congestion. Congestion frequently occurs during evacuation as bottleneck areas cause people to gather faster than the evacuation capacity of the exits. When the entire crowd is observed, external pressure (disaster or danger) compresses the crowd continuously in bottleneck areas, causing individuals' distance to become smaller and smaller. At this point, it is easy for the number of people at the exit to reach equilibrium and form an arch, and the duration of this phenomenon has a direct impact on congestion time and a negative impact on evacuation outcomes (Li et al., 2019). As the angle of inclination increases, people require more energy and time to adapt to the environment and adjust their body state accordingly, making them less capable of breaking the arch equilibrium, resulting in a greater probability that ΔT becomes longer.

Discussion

In terms of crowd emergency management, maintaining a certain social distance between individuals is crucial during normal scenarios, which is reflected by the inter-peer force $\boldsymbol{f}_{ij}$ in the basic social force model. However, in the presence of danger, panicked individuals may exhibit a shortening of social distance and may even push and crowd with others, which is a phenomenon that has received significant attention both in real-life situations and modelling simulations (Andrés-Thió et al., 2021).

Through the simulation analysis, it becomes evident that increasing the proportion of competitive individuals can lead to a reduction in the total evacuation time. However, it is worth noting that when the parameter α reaches 0.5, the evacuation time might experience its most significant decrease. Further statistical analysis of the simulation results reveals that a higher α is more likely to disrupt the equilibrium at the exit, potentially causing congestion. In inclined scenarios, increasing α can indeed accelerate the evacuation process to a certain extent. However, individuals in such scenarios must expend more effort and time to navigate the challenges posed by the inclined ship's impact on their movement. Consequently, despite heightened competitive desires compared to scenarios without an inclination angle, the total evacuation time may not be effectively shortened.

Based on the simulation results of the proposed model in this study, it is believed that including a reasonable number of competitive people is beneficial to the overall efficiency and evacuation results of human evacuation from ships. From the perspective of crowd management, more attention should be paid to individuals in congested areas during the evacuation process. Under the premise of ensuring safety, appropriately increasing the proportion of competitive people can improve the flow rate at the exit. Additionally, the impact of ship inclination on human movement should be fully considered when formulating evacuation strategies. The crew should be arranged to organize and guide the evacuee to avoid stampedes caused by excessive panic among individuals.

Conclusion

This study proposes a social force evacuation model nested with a real-time competitive degree assessment system to study human competitive behaviour in evacuation scenarios of inclined ships. In addition to considering the effect of ship inclination on human movement, the model redefines the perceived area of competitive people in the evacuation process and calculates the competitive degree in real-time at each time step using crowd density and inclined angle as input parameters. To provide a more detailed description of the human evacuation process in an inclined ship, the effect of different inclination angles and the proportion of competitive people on the evacuation result is analysed using the dining room of a ship as a case study.

This study provides a comprehensive exploration of the influence of competitive behaviour on the evacuation process, taking into account the severity of the accident. Additionally, the real-time assessment system for measuring human competitiveness ensures that simulation results closely approximate real-world conditions. Through quantitative analysis of the simulation outcomes, the study identifies the factors constraining the evacuation process, thus offering valuable insights for the development of evacuation strategies on inclined ships. The findings from this research can serve as a foundation for future work on human evacuation aboard ships, ultimately enhancing the safety of passenger vessels.

However, this work has some limitations due to the lack of validation data. Firstly, the model only considers scenarios where the ship maintains a single inclination angle and does not fully account for the effect of changes in inclination angle on human movement. Secondly, the analysis only covers the evacuation process in a single room and not the overall evacuation process of a full-size ship. Finally, the model does not integrate competitive behaviours such as group behaviours and helping behaviours that may occur during the evacuation process. These limitations will be addressed in future work.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1 Rules for assessing the competitive degree.

No	Inclination angle	Density	Competitive
1	S	L	VW
2	S	M	W
3	S	H	M
4	M	L	W
5	M	M	M
6	M	H	S
7	L	L	M
8	L	M	S
9	L	H	VS