

Article

Simulating Evacuation on Inclined Offshore Platforms with an Improved Social Force Model

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Abstract

Offshore platforms are particularly vulnerable to inclination or capsizing during extreme weather conditions, such as strong winds, high waves, and powerful currents. These scenarios pose significant risks to offshore employees, making efficient evacuation strategies crucial. This study investigates evacuation processes on inclined offshore platforms, considering heel angles from 0° to 20° and trim angles from −20° to 20°, focusing on how platform inclination affects evacuation speed and overall evacuation time. To improve simulation accuracy, an Improved Social Force Model is proposed, incorporating both inclination-induced forces and attraction forces to better represent evacuation dynamics on inclined platforms. Simulation results indicate that evacuation time increases significantly when inclination angles exceed 15°, with longitudinal forces having a greater impact on stairway evacuations compared to heel forces. The findings offer valuable guidance for improving evacuation protocols on inclined offshore platforms.

Keywords: offshore platform; inclination; offshore employee evacuation; improved social force model

1. Introduction

Climate change is projected to increase the frequency and intensity of extreme weather events, such as typhoons, which pose significant challenges to offshore platform operations [1]. Consequently, incidents involving inclined offshore platforms are becoming more frequent. For example, on 3 May 2021, the “NAGA 7” jack-up drilling platform operated by Velesto Energy tilted by about 10 degrees and eventually sank due to deformation of its support frame. Similarly, on 25 July 2021, the “Sheng Ping 001” offshore construction platform in Huizhou City, China, tilted due to adverse wind and wave conditions. These incidents highlight the substantial risks posed by harsh marine environments and the severe losses they can cause. According to the study by Zubaidah [2], platform inclination caused by wind and wave forces is the second most common type of accident, following fire-related incidents. The increasing frequency of platform tilting and capsizing underscores the need for safe, timely, and orderly evacuation strategies.

Evacuation is a critical measure to reduce casualties during offshore emergencies [3]. However, evacuations from offshore platforms present unique challenges, including confined spaces, narrow passages, multi-level structures, and specialized assembly areas [4].



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These characteristics differ markedly from those of land-based buildings and seagoing vessels, and passenger ships are emphasized in international maritime regulations as representative maritime references because their high passenger capacity, multi-deck configurations, and internationally standardized evacuation provisions make them widely adopted benchmark cases for evacuation studies [5]. All ships and offshore installations are subject to internationally recognized requirements for abandonment arrangements and emergency drills; however, passenger ships are often used as benchmark cases because their high occupant loads are typically accompanied by wider evacuation corridors, high-capacity standardized life-saving appliances, and more prescriptive evacuation-related provisions, whereas land-based buildings provide stable evacuation routes and usually allow evacuees to exit directly to open ground. In contrast, during extreme-weather or accident scenarios offshore installations may develop sustained heel or trim driven by wind-wave loads, restraint conditions, or structural damage; such persistent inclinations can directly impair pedestrian stability, walking speed, and route choice on exposed decks and stairways. Furthermore, although both ships and offshore installations require mustering before embarkation, evacuation on offshore platforms is often constrained by a limited number of exposed muster points and by the reduced availability of these points under sustained heel or trim, which can markedly increase congestion and evacuation uncertainty. These distinctions, especially under inclination scenarios, highlight the necessity of developing evacuation models specifically tailored to the offshore platform environment.

This study aims to examine the evacuation process on tilted offshore platforms by improving the Social Force Model (SFM). We analyze the impact of varying inclination angles on evacuation speed and time, introducing new forces to represent platform inclination to more accurately simulate complex evacuation scenarios. The proposed model provides a theoretical foundation and practical data to support emergency evacuation strategies on tilted platforms.

The main contributions of this paper are as follows:

1. An improved SFM for evacuations on inclined platforms is proposed, incorporating inclination and attraction forces. The model can be used to simulate offshore employees behavior on inclined platform. It demonstrates that evacuation times increase significantly when inclination angles exceed 15° .
2. Simulation results indicate that inclination angles substantially affect evacuation speed. Longitudinal forces have a stronger impact on stairway evacuations than heel forces, while trimming by the bow results in the longest evacuation times.
3. Both simple and complex evacuation scenarios are simulated, showing that single-deck offshore employees distributions reduce the evacuation efficiency, while double-deck distributions improve it. Higher evacuation speeds significantly shorten evacuation times, especially under extreme inclination conditions.

The remainder of the paper is organized as follows: In Section 2, relevant literature on offshore platform inclination and evacuation is reviewed. Section 3 introduces the improved SFM and outlines the model's computational framework. Section 4 presents the model verification process. Section 5 discusses the simulation results. Finally, Section 6 summarizes the conclusions and practical implications of the study.

2. Related Works

Evacuation safety in offshore and maritime environments has long been a critical research area due to the high risks associated with fire, flooding, and structural failure. Numerous studies have investigated how environmental hazards and structural conditions affect evacuation dynamics. For example, Sun et al. [6] and Wang et al. [7] analyzed how fire and smoke conditions affect evacuee behavior, while Fang et al. [8,9] investigated

the effects of environmental complexity on pedestrian movements. These works provide valuable insights into hazard-induced evacuation risks.

Recent studies have also emphasized the impact of structural inclinations on evacuation efficiency. For example, Hu et al. [10] reported that evacuation efficiency deteriorated rapidly once heel angles exceed 15°, and Fang et al. [11] reached similar conclusions, identifying critical thresholds of inclination beyond which safe evacuation is severely compromised. These findings highlight the necessity of accounting for platform or vessel inclinations in evacuation analysis, yet an important gap remains: few evacuation models explicitly combine SFM-style social-psychological interaction with physics-based modifications for sustained inclination, surface friction and slip risk. Existing approaches either treat inclination as a perturbation to walking speed without changing interaction mechanics or import empirical speed-reduction factors without coupling them to local forces and stability criteria. This disconnect limits the predictive power of simulations for platforms that experience inclination during emergencies.

A variety of modeling approaches have been developed to study evacuation safety, including cellular automata, agent-based, and continuum-based flow models. Although each approach provides valuable insights, they often struggle to capture both microscopic pedestrian interactions and macroscopic evacuation dynamics simultaneously. The SFM, in contrast, has been proven effective in reproducing realistic pedestrian behaviors such as lane formation, bottleneck congestion, and panic effects [12,13]. Compared with other approaches, the SFM offers a flexible and behaviorally grounded framework that balances physical and psychological factors, making it well suited for evacuation studies in complex environments. For this reason, the present study adopts and extends the SFM to analyze offshore evacuation scenarios.

The SFM has been widely applied and extended to model diverse evacuation behaviors. Building on the original formulation [12], researchers have incorporated factors such as panic dynamics, group interactions, and spatial constraints. Applications to high-rise buildings [14], underground stations [15], and passenger ships [11] consistently demonstrate its ability to reproduce realistic evacuation patterns. Such methodological advances provide a solid foundation for adapting the SFM to maritime evacuation analysis.

In summary, prior work provides a solid foundation in terms of SFM formulations but does not yet yield a unified modeling framework for inclined offshore platforms. These gaps motivate the present study, which develops an improved SFM that integrates inclination-driven gravitational effects, slope-dependent friction and stability constraints, and scenario-specific evacuation rules to better predict offshore employees movement and bottleneck formation on tilted decks.

3. Methodology

3.1. Social Force Model

The SFM, originally proposed by Helbing and Molnar [12] and later expanded by Helbing et al. [16], describes pedestrian movement based on Newtonian mechanics. In this framework, a pedestrian's motion results from the combination of several forces, including self-driving motivation, social interactions, and resistance from the surrounding environment. Over the past two decades, the SFM has been extensively applied to diverse evacuation scenarios, including high-rise buildings, underground stations and passenger ships, demonstrating its robustness and validity across different environments. These proven applications confirm that the SFM provides a solid methodological foundation for analyzing evacuation processes in complex and constrained settings.

The total force acting on pedestrian i is defined as the sum of main components: the self-driving force, the interaction forces with other pedestrians, and the resistance forces from obstacles. Mathematically, this is expressed as

$$m_i \frac{d\vec{v}_i}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_W \vec{f}_{iw} \quad (1)$$

where m_i is the mass of pedestrian i ; i , j , and w represent the pedestrians, neighboring pedestrians, and obstacles, respectively. $\vec{v}_i$ is the real-time speed of pedestrian i , $\vec{f}_i^0$ represents the self-driving force, $\vec{f}_{ij}$ represents the repulsive force between pedestrians i and j , and $\vec{f}_{iw}$ represents the repulsive force between pedestrian i and obstacle w .

The self-driving force $\vec{f}_i^0$, which guides pedestrians toward desired exits, is given by

$$\vec{f}_i^0 = m_i \frac{v_i^0(t) \vec{e}_i^0(t) - \vec{v}_i(t)}{\tau_i} \quad (2)$$

where $v_i^0(t)$ denotes the desired speed of pedestrian i , $\vec{e}_i^0(t)$ denotes the desired movement direction, $\vec{v}_i(t)$ denotes the current speed, and τ_i represents the reaction time.

This term represents the driving force that propels evacuees toward the exit or muster station at their preferred walking speed. The parameter τ_i denotes the reaction time required for an evacuee to adjust their current speed to the desired one, thus linking human perception and decision-making delays to physical movement.

The interaction force $\vec{f}_{ij}$ between pedestrians i and j combines psychological repulsion, collision, and friction forces.

$$\vec{f}_{ij} = A_i \exp[(r_{ij} - d_{ij})/B_i] \vec{n}_{ij} + kg(r_{ij} - d_{ij}) \vec{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ij}^t \vec{t}_{ij} \quad (3)$$

where $A_i \exp[(r_{ij} - d_{ij})/B_i] \vec{n}_{ij}$ represents the psychological repulsive force, which keeps pedestrian i away from other pedestrians, A_i is a positive constant reflecting the psychological tendency to maintain personal space; B_i is a constant describing the effect of distance on the repulsive force based on the studies of pedestrian density in enclosed environments; r_{ij} is the sum of radii of pedestrians i and j , and d_{ij} is the distance between pedestrians i and j . Moreover, $kg(r_{ij} - d_{ij}) \vec{n}_{ij}$ and $\kappa g(r_{ij} - d_{ij}) \Delta v_{ij}^t \vec{t}_{ij}$ are, respectively, the collision force and friction force, with k and κ as the collision coefficient and friction coefficient, and g is a “ramp function” that ensures collisions and friction occur only during physical contact, with its value defined as shown in Equation (5). The associated coefficients are derived from physical interaction models [16] to simulate body contact and sliding effects. $\vec{n}_{ij}$ is the normalized vector pointing from the pedestrian j toward the pedestrian i , $\vec{t}_{ij}$ represents the tangential direction, and Δv_{ij}^t denotes the tangential speed difference.

The force $\vec{f}_{iw}$ acting between pedestrian i and an obstacle w is analogous to $\vec{f}_{ij}$, and can be expressed as

$$\vec{f}_{iw} = A_i \exp[(r_i - d_{iw})/B_i] \vec{n}_{iw} + kg(r_i - d_{iw}) \vec{n}_{iw} - \kappa g(r_i - d_{iw}) (\vec{v}_i \cdot \vec{t}_{iw}) \vec{t}_{ij} \quad (4)$$

where r_i is the radius of pedestrian i , d_{iw} is the distance between the pedestrian i and an obstacle w , $\vec{n}_{iw}$ is the normalized vector pointing from the obstacle w toward pedestrian i , $\vec{v}_i$ is the real-time speed of pedestrian i , and $\vec{t}_{iw}$ represents the tangential direction.

The function $g(x)$ is a piecewise function, which is expressed as

$$g(x) = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (5)$$

where x is the independent variable, corresponding to $r_{ij} - d_{ij}$ in Equation (3) and $r_i - d_{iw}$ in Equation (4).

3.2. Improved SFM for Evacuation Analysis

The SFM has been widely applied to studies of pedestrian dynamics in various environments, including shopping malls, high-rise buildings, and ships [17]. The original SFM has been improved by incorporating factors such as panic [18], psychological stress [19], and tension effects [20]. In this study, the original SFM is further improved to analyze offshore employees' evacuation on inclined offshore platforms. When a platform tilts, gravitational components along the slope affect offshore employees' balance and movement. Figure 1 illustrates the forces acting on an offshore employee under heel and trim conditions.

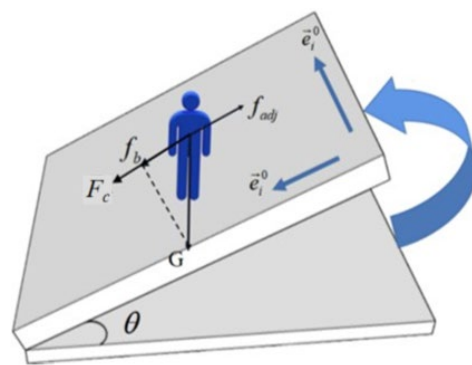


Figure 1. The force diagram for an offshore employee on a tilted platform.

In this study, evacuees are assumed to maintain upright walking postures under all inclination conditions, with stability preserved through adjustment forces. Adaptive behaviors commonly observed in real incidents such as crawling or using handrails are not explicitly modeled.

For offshore employees on inclined surfaces, the platform's inclination generates an inclining force f_b and a self-adjustment force f_{adj} . F_c is the combined force of the two. The magnitude of the adjustment force is based on the fitting data from Fang et al. [21] and further refined through simulation. The relevant equations are presented in Equations (6)–(9).

It is worth noting that the heel angle θ and the trim angle ϕ are defined as signed quantities and may take positive or negative values. In this study, $\theta > 0$ denotes a starboard-down heel and $\theta < 0$ as port-down heel. $\phi > 0$ as bow-down trim and $\phi < 0$ as stern-down trim. The inclination force $\vec{f}_b$ acts along the local downslope direction and therefore reverses direction when the sign of θ or ϕ changes. The total inclination force is decomposed into a heel component $\vec{f}_{b,h}$ and a trim component $\vec{f}_{b,t}$, $\vec{f}_b = \vec{f}_{b,h} + \vec{f}_{b,t}$. The self-adjustment force f_{adj} is defined to act upslope, opposing $\vec{f}_b$.

When the platform experiences a heel, the heel-induced component of the inclination force acting on an offshore employee is expressed as

$$\vec{f}_{b,h} = G \times \sin\theta \quad (6)$$

where G denotes the gravitational force acting on an individual. For computational convenience, the gravitational acceleration is taken as $g = 10 \text{ m/s}^2$, and θ represents the platform heel angle.

This additional term captures the effect of platform inclination on evacuee movement. When the platform tilts, gravity introduces a downslope component that can either assist or hinder offshore employees motion depending on the travel direction. For instance, evacuees moving downhill benefit from gravitational acceleration and achieve higher speeds, whereas uphill movement demands greater effort, leading to slower evacuation and potential congestion.

Drawing on the findings of Fang [11,21], the inclination adjustment force was partially corrected through simulation experiments. The coefficients of the self-adjustment force $\vec{f}_{adj}$ are determined using the piecewise linear fitting approach proposed by Fang et al. These functions describe offshore employees' proactive balance-control responses, whereby individuals shift their center of gravity to counteract the inclination force $\vec{f}_b$. Based on experimental observations from the HSVA and AENEAS datasets [22], this adjustment mechanism exhibits distinct behavioral transitions at inclination angles of 15° and 25° , which are reflected in the changes in fitted gradients in the corresponding equations. The corresponding formulas are presented in Equations (7)–(10). The heel adjustment force $\vec{f}_{adj}(\theta)$ varies with the heel angle (θ) according to the piecewise function

$$\vec{f}_{adj}(\theta) = \begin{cases} \vec{f}_{b,h} & 0^\circ \leq \theta < 5^\circ \\ 1/6 \vec{f}_{b,h} & 5^\circ \leq \theta < 15^\circ \\ 0.9649 \vec{f}_{b,h} - 130.790 & 15^\circ \leq \theta < 20^\circ \\ 0.7121 \vec{f}_{b,h} - 71.636 & 20^\circ \leq \theta < 25^\circ \\ 1.1163 \vec{f}_{b,h} - 192.884 & 25^\circ \leq \theta \leq 30^\circ \end{cases} \quad (7)$$

When the offshore platform is trimmed, the force experienced by offshore employees is

$$f_{b,t} = G \times \sin\phi \quad (8)$$

The trim adjustment force $f_{adj}(\phi)$ under longitudinal inclination varies with the trim angle (ϕ) as given by

$$\vec{f}_{adj}(\phi) = \begin{cases} -1.4404 \vec{f}_{b,t} & -30^\circ \leq \phi < -15^\circ \\ -0.2 \vec{f}_{b,t} & -15^\circ \leq \phi < 0^\circ \\ 0.2 \vec{f}_{b,t} & 0^\circ \leq \phi < 10^\circ \\ 0.1130 \vec{f}_{b,t} + 9.550 & 10^\circ \leq \phi < 25^\circ \\ 1.4404 \vec{f}_{b,t} - 314.046 & 25^\circ \leq \phi \leq 30^\circ \end{cases} \quad (9)$$

Incorporating these inclination effects, the improved SFM can be expressed as

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_W \vec{f}_{iw} + \vec{f}_b + \vec{f}_{adj} \quad (10)$$

The inclusion of inclination forces alters the spatial distribution of offshore employees during evacuation. As heel and trim angles increase, evacuees disperse differently and exhibit more goal-oriented movement toward exit locations under larger inclinations. Larger inclinations significantly impede movement, resulting in longer evacuation times.

Previous studies using the SFM have observed that evacuees often develop expectations about exit locations during emergencies. To reflect this behavior, we introduce exit attraction forces that guide evacuees toward preferred exits. In practice, evacuees often move in small groups; however, traditional SFM formulations treat individuals independently, overlooking the effects of group cohesion.

To address this limitation, we introduce group attraction forces f_{ij}^{att} (see Equation (11)) and exit attraction forces $\vec{f}_{iE}$ (Equation (12)). During evacuation from a tilted platform, individuals tend to follow others, driven by the belief that others possess better knowledge of escape routes or that remaining in groups enhances safety [19,23]. Group attraction (f_{ij}^{att}) simulates this tendency, while exit attraction ($\vec{f}_{iE}$) represents the evacuees' goal-oriented movement toward exits. As platform inclination increases, evacuees are assumed to focus more strongly on exit locations, thereby compensating for the physical challenges posed by the slope.

Group attraction forces [19] are given by

$$f_{ij}^{att}(t) = C_{ij} \exp\left[\frac{(r_{ij} - d_{ij})}{D_{ij}}\right] \vec{n}_{ij} \quad (11)$$

where C_{ij} is the attraction intensity with direction from i to j ; D_{ij} is the attraction range. These two parameters characterize the tendency of individuals to follow others during emergencies.

To represent the influence of exits on offshore employees movement, we introduce an exit-directedness weighting function $\mu(\theta)$, which characterizes evacuees' increased goal-oriented tendency to move toward known or visible exits under physically challenging inclination conditions.

$$\vec{f}_{iE}(t) = \mu(\theta) G_{iE} \vec{n}_{iE}(t) \quad (12)$$

where G_{iE} is an attraction constant, adjusted based on route familiarity and visibility of exits under inclination condition [21]; $\vec{n}_{iE}(t)$ is the unit vector pointing toward the exit; $\mu(\theta)$ is the path familiarity function:

$$\mu(\theta) = \begin{cases} 1.0 & 0^\circ \leq \theta \leq 15^\circ \\ 1.2 & 15^\circ < \theta < 25^\circ \\ 1.8 & 25^\circ \leq \theta \leq 30^\circ \end{cases} \quad (13)$$

The threshold value for the exit-directedness weighting function $\mu(\theta)$ is set based on experimental studies by Sun et al. [6] and Valanto et al. [22], which show that walking becomes more difficult when the inclination angle exceeds 15° , and even more difficult when the angle exceeds 25° .

Therefore, the improved SFM for evacuation on inclined offshore platforms, which incorporates exit attractiveness, is formulated as follows:

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_W \vec{f}_{iw} + \vec{f}_b + \vec{f}_{adj} + \vec{f}_{ij}^{att} + \vec{f}_{iE} \quad (14)$$

where f_b denotes inclining force, f_{adj} denotes trim adjustment force, f_{ij}^{att} denotes group attraction forces and $\vec{f}_{iE}$ denotes exit attraction forces.

In this study, offshore employees are assumed to maintain balance through adjustment forces even at high inclination angles. This implies that sliding or falling behaviors, which may occur at extreme inclinations ($>25^\circ$), are not explicitly modeled. The assumption

is reasonable for moderate inclinations where individuals can compensate by leaning or adjusting their gait, but it may underestimate risks under severe inclination conditions.

In summary, the incorporation of these forces completes the formulation of the improved SFM, which now systematically accounts for the principal physical (inclination, adjustment), psychological (repulsion), and socio-cognitive (attraction) factors influencing evacuation dynamics on inclined offshore platforms. The robustness of this integrated framework is subsequently substantiated through its calibration and verification against internationally recognized benchmarks, as detailed in the following section.

4. Verification of the Improved SFM

To ensure the reliability of the proposed model, a two-step validation strategy is adopted in accordance with the established maritime safety guidelines. Firstly, the model is quantitatively validated against the standard IMO [24] benchmark (Test 6) under non-inclined conditions to verify its fundamental crowd dynamics. Secondly, qualitative sensitivity analysis is conducted under inclined conditions to confirm that the model reproduces physically plausible behaviors—such as lateral drift and speed attenuation—prior to its application to the full offshore platform scenario.

4.1. Validation Against IMO Benchmark Test 6

To assess the reliability of the improved model in handling complex geometries, IMO Test 6, as specified in the IMO Guidelines (MSC.1/Circ.1238) [24] is adopted. This benchmark is specifically designed to verify a model's ability to simulate offshore employees movement around corners without producing unrealistic behaviors, such as wall penetration or agent overlap.

The simulation scenario consists of a 2 m wide corridor with a 90° corner (see Figure 2). 20 evacuees were initialized at the corridor entrance, with a uniform desired walking speed of 1.0 m/s assigned to all agents. The simulation is conducted under standard static conditions (0° heel and 0° trim) to provide a baseline for validating fundamental crowd dynamics and boundary interactions.

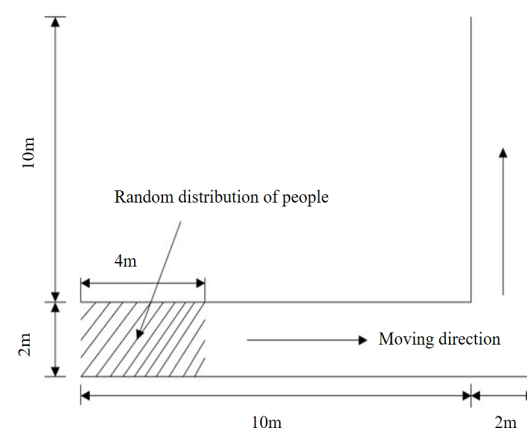


Figure 2. IMO 6th test scenario.

Ten independent simulation runs are performed. The results yielded an average evacuation time of 27.51 s. In all simulations, evacuees successfully negotiated the corner without exhibiting unrealistic behaviors such as wall intrusion or boundary violations. These results demonstrate that the fundamental driving and repulsive force components of the improved social force model operate correctly under standard maritime protocol conditions.

4.2. Qualitative Sensibility Analysis Under Inclination

To validate the improved SFM, two benchmark scenarios defined by the International Maritime Organization (IMO) that are the 6th and 9th test scenarios, are selected [24]. These scenarios are widely recognized for assessing evacuation performance under maritime conditions and therefore provide a robust basis for model verification.

The IMO 6th benchmark test is selected to validate the improved SFM, as it is widely used to evaluate evacuation through a corridor with a corner and to assess offshore employees behavior in constrained pathways ([24], Figure 2). In this study, the scenario was configured with 20 evacuees, a heel angle of 10° , a trim angle of -10° , and an initial speed of $v_0 = 1.0$ m/s. The improved SFM was employed to simulate the evacuation, verifying that all participants could successfully navigate the corner and reach the exit without unrealistic behaviors such as wall penetration.

Simulation results are shown in Figures 3 and 4. The evacuation in the 6th test is successful, as offshore employees navigate the exit without any issues such as overcrowding or breaching barriers. These results align well with empirical expectations and prior IMO validation studies, confirming that the improved SFM can accurately reproduce evacuee flow patterns in cornered corridors.

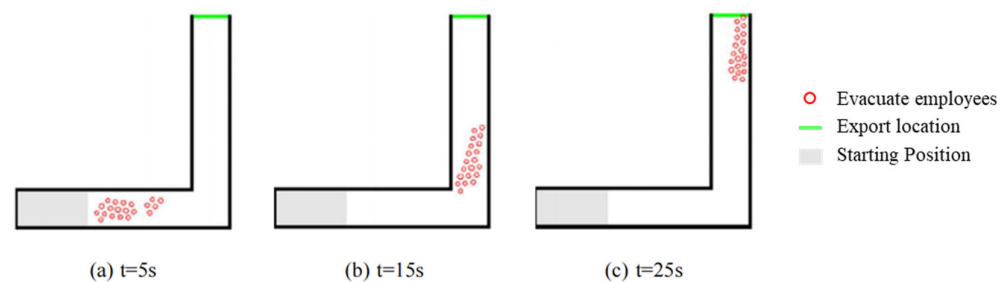


Figure 3. IMO 6th test verification process.

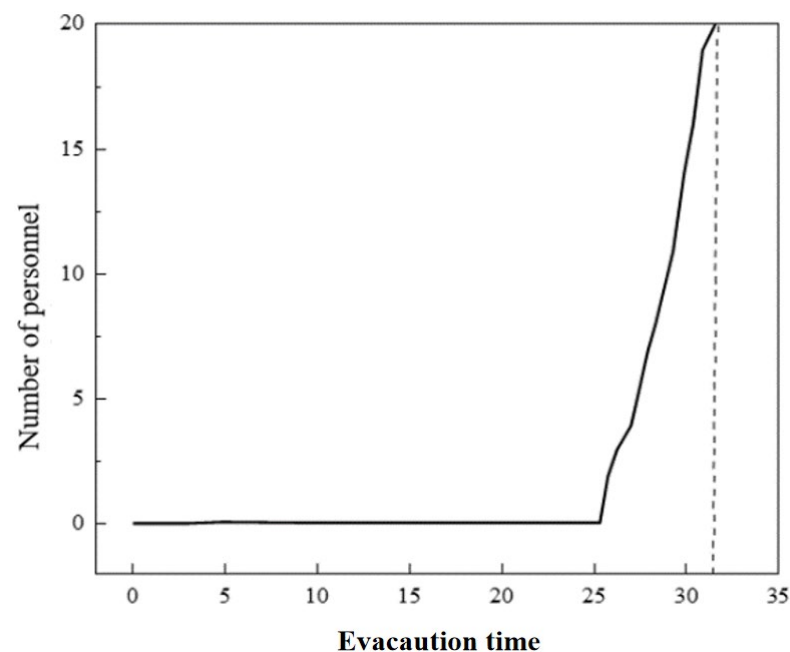


Figure 4. IMO 6th test evacuation time.

IMO's test 9 constructs a large public space scenario with four exits, as shown in Figure 5, to assess the evacuation time of 1000 people and verify that the model generates realistic behavior [24]. The verification procedure is as follows: firstly, the total evacuation

time is measured under the four-exit condition; secondly, exits 3 and 4 are closed, and the evacuation time is measured under the two-exit condition. The expected outcome is that the evacuation time with two exits will be approximately twice that of the four-exit case.

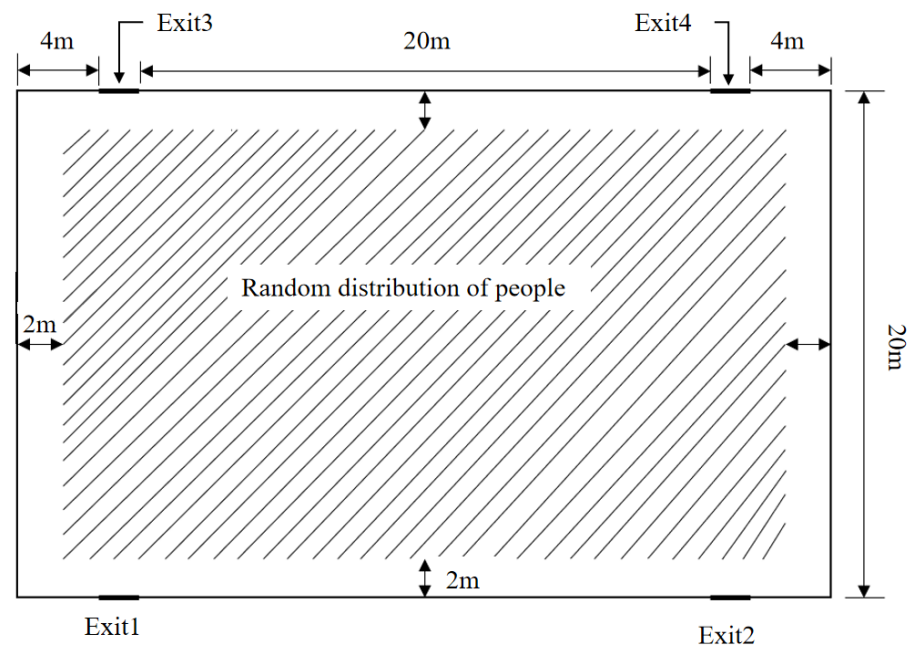


Figure 5. IMO 9th test scenario.

In this section, the test is conducted under a heel and trim angle of 5° . Stepwise verification is performed as follows:

Step 1: Evacuate 1000 individuals through four exits at $v_0 = 1.0$ m/s. The evacuation process is shown in Figure 6.

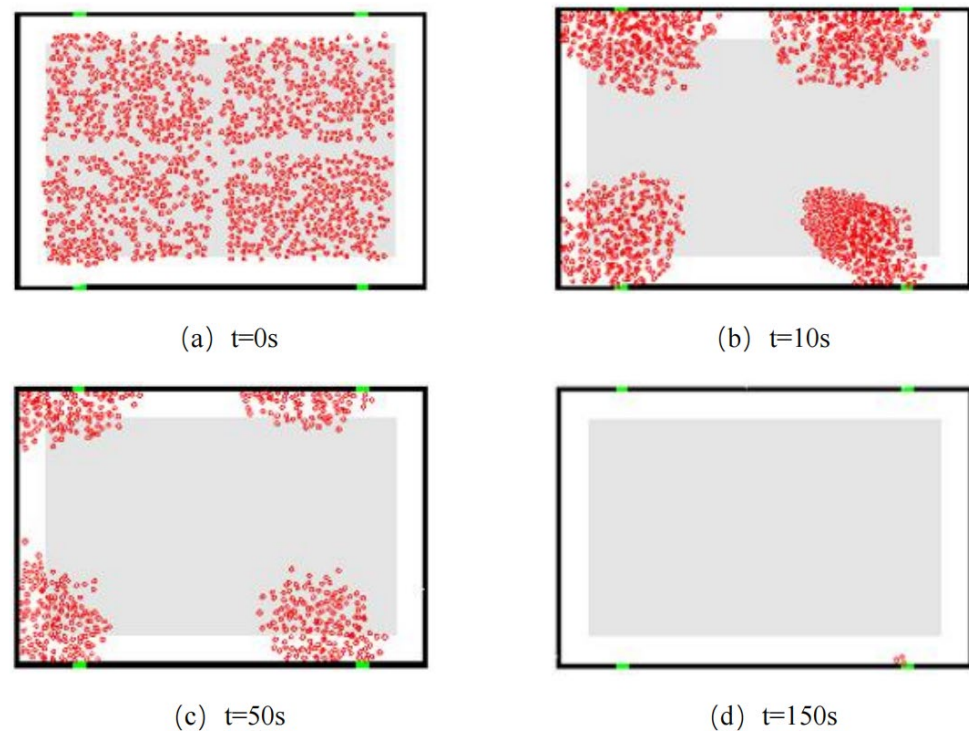


Figure 6. Simulation snapshots of evacuation through four exits under 5° heel and trim conditions.

Step 2: Close exits 3 and 4 under the same conditions. The evacuation process is shown in Figure 7.

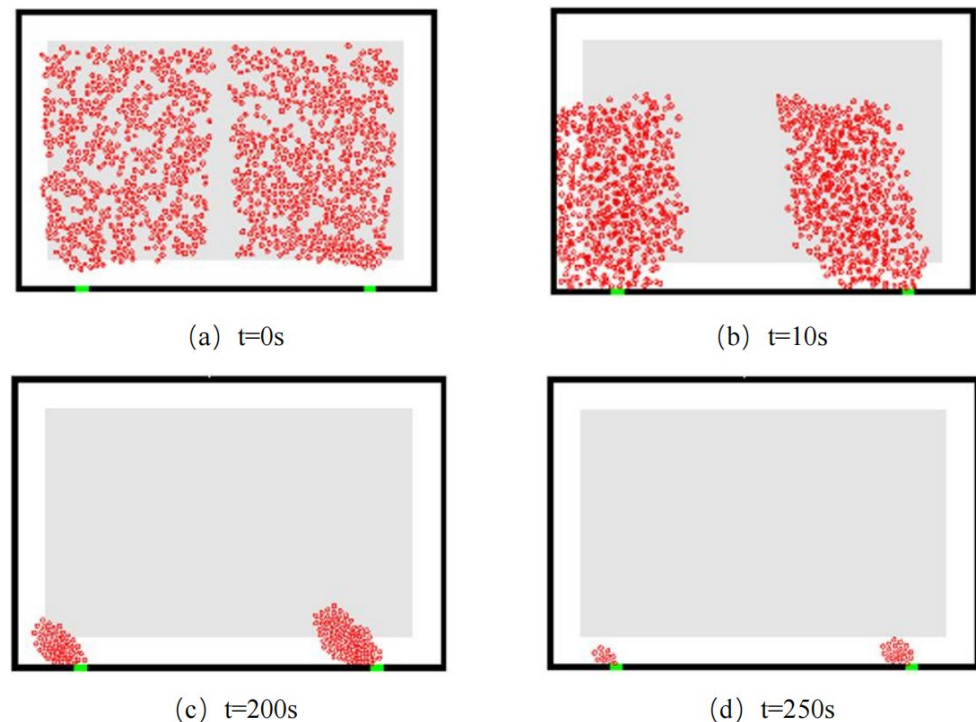


Figure 7. Evacuation process with two exits closed.

The corresponding evacuation time is summarized in Figure 8. The results show that the improved SFM reproduces realistic offshore employees movement and correctly reflects the increased evacuation time when the number of exits is reduced.

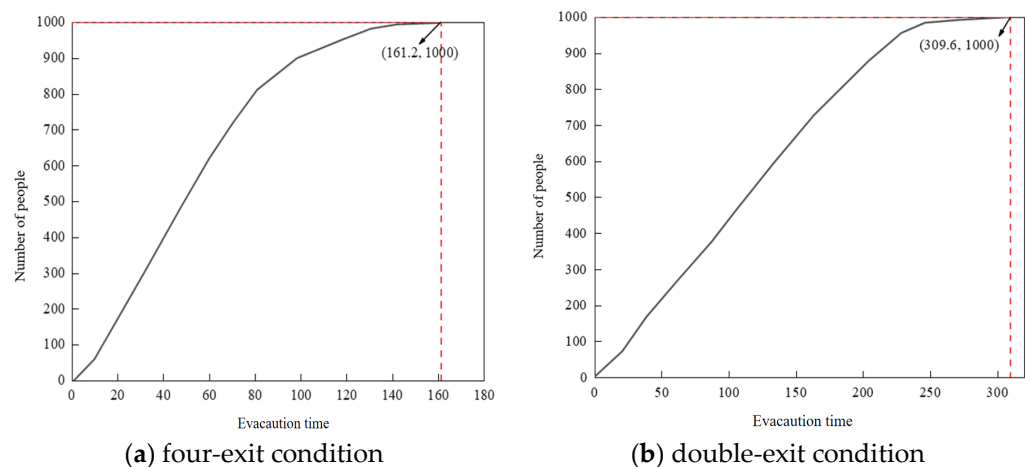


Figure 8. IMO 9th Test Evacuation Results.

5. Evacuation Simulation on Offshore Platform

This section presents evacuation simulations on an offshore platform located in the South China Sea. Both simplified environments (e.g., corridors, stairways) and complex environments (e.g., multi-story living quarters) are simulated to evaluate the performance of the improved SFM. The objectives of these simulations are as follows:

1. To analyze evacuation patterns under varying inclination angles and assess how platform inclination affects accessibility and evacuation efficiency.

2. To investigate how desired evacuation speeds and offshore employees distribution influence overall evacuation outcomes.

The case-study installation is a Semi-submersible drilling platform. As illustrated in Figure 9, it consists of a two-story accommodation block, drilling and workover rigs, mechanical and oil-production facilities, life-saving appliances, and a helicopter deck.

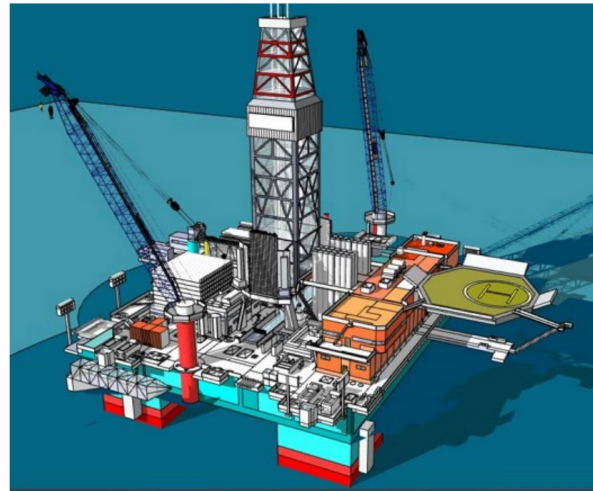


Figure 9. Offshore platform in the South China Sea.

5.1. Dual-Exit Corridor Scenarios

In this section, the evacuation process is simulated in a dual-exit corridor scenario within the living quarters of an offshore platform. In this scenario, 100 individuals evacuate through two exits on an inclined platform (10° heel and 5° trim) with an average walking speed of 1.5 m/s. These parameters are chosen to represent a medium-scale evacuation, emphasizing the effects of platform inclination while avoiding excessive crowding. In subsequent sections, varying group sizes are employed to reflect the typical occupancy of specific areas on offshore platforms. Evaluating various group sizes enables the improved SFM to be tested across a spectrum of density conditions, thereby improving the model's robustness and generalizability.

Remark 1. Unless otherwise stated, each evacuation scenario is simulated for ten independent runs with different random initial distributions, and the evacuation time is reported as mean $\pm$ standard deviation (SD).

Three models are compared: the original SFM, the inclined SFM accounting only for inclined forces and the improved SFM integrating inclined forces with attraction forces.

Original SFM (Figure 10a): Offshore employees were evenly distributed, and evacuations proceeded smoothly. After 25 s, individuals at the rear began to move. The average evacuation time across 10 trials was 29.88 ± 1.38 s (mean $\pm$ SD). This baseline scenario does not include inclination-induced forces and therefore represents an idealized flat-surface evacuation.

Inclined SFM (Figure 10b): The effects of inclination became evident within the first 5 s. Lateral drift induced by the heel angle caused offshore employees to accumulate near corners, resulting in pronounced local congestion and a substantially delayed evacuation. Under the same 10° heel condition, the average evacuation time increased to 103.20 ± 5.14 s.

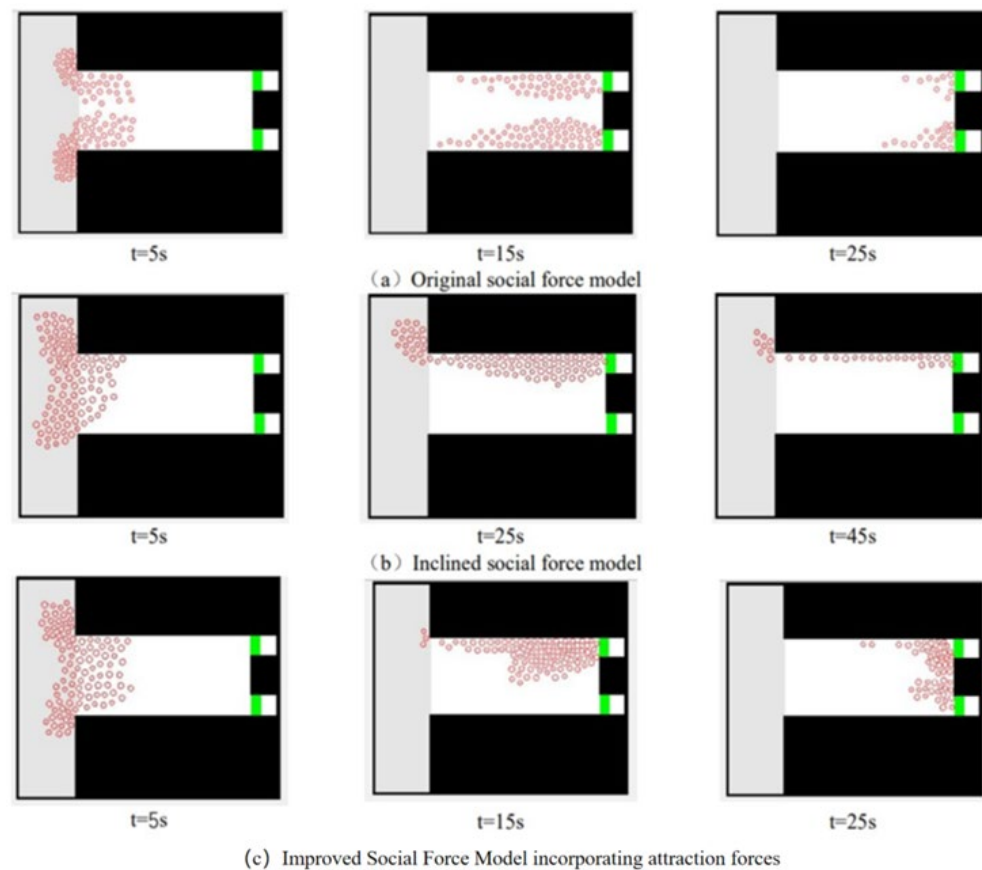


Figure 10. Evacuation time under different inclination angles.

Improved SFM (Figure 10c): When attraction forces are introduced, changes in evacuee spatial distribution and corner congestion were observed relative to the inclined SFM. It is emphasized that these forces are included to represent behavioral interactions rather than to compensate for the physical effects of inclination. Under the same 10° heel condition, this behavioral modification resulted in a more balanced exit usage and reduced the average evacuation time from 103.2 ± 5.14 s (inclined SFM) to 43.5 ± 1.23 s. These results indicate that the attraction terms influence evacuation outcomes by altering crowd distribution and mitigating inclination-induced congestion patterns.

In the original model, evacuees were initially distributed closely together. However, approximately 25 s, individuals at the rear became more dispersed. Overall, the evacuation proceeded smoothly, with offshore employees dividing into two groups and utilizing both exits. This behavior is consistent with real-world expectations.

In the inclined SFM, the effects of heel became apparent by $t = 5$ s. Individuals began moving along both the inclination and the heel directions. Those located in the lower part of the area moved upward, which caused evacuees in the upper section to become temporarily stranded at a corner, waiting for those ahead to pass. Furthermore, most evacuees preferred the exit on the inclined side, leading to slower evacuation as the alternative exits appeared less attractive.

In contrast, the improved SFM incorporating attraction forces yielded an average evacuation time of $t = 43.5 \pm 1.23$ s across 10 simulations. The inclusion of attraction forces promoted a more balanced distribution of evacuees and accelerated the overall evacuation process. Near the exits, the attraction effect enabled individuals to counteract the influence of inclination and use both exits effectively.

Compared with the inclined SFM, the addition of attraction forces significantly reduced evacuation delays, minimized congestion, and improved the overall evacuation dynamics.

This behavior more closely mirrors the expected actions of offshore employees in real-world evacuation scenarios.

5.2. Stairway Evacuation Scenarios

Stairways present unique challenges during evacuation due to their slope and limited width, both of which are exacerbated by platform inclination. In the improved SFM (Equation (10)), global platform inclination is captured by forces $\vec{f}_b$ and $\vec{f}_{adj}$. However, on stairs, platform inclination interacts with the stair slope, requiring a more precise formulation.

Therefore, to accurately simulate evacuation on an inclined platform, the generic inclination force $\vec{f}_b = G \times \sin\theta$ (Equations (6) and (8)) must be replaced with a more precise calculation that resolves the force components specific to the stair's orientation. For offshore employees moving on stairs, a local stair coordinate is defined on the stair surface. Let α denote the stair pitch angle (the angle between the stair direction and the horizontal plane). The platform attitude is characterized by heel θ and trim ϕ , which induce effective gravity components along their respective directions. Within the inclination range considered in this paper, we use the small-angle approximation, expressing these components compactly as proportional to $\tan\theta$ and $\tan\phi$. By projecting the attitude-induced gravity components onto the stair surface, the stair-specific contributions of heel and trim are obtained, as given in Equation (15).

$$\begin{aligned} F_h &= G \times \sin\alpha \times \tan\theta \\ F_t &= G \times \cos\alpha \times \tan\phi \end{aligned} \quad (15)$$

where F_h is heel force acting on evacuees on the staircase; F_t is trim force acting on evacuees on the staircase; α is stair angle (30°); θ and ϕ is platform heel and trim angles. $G = mg$ is the offshore employee's weight. Equation (15) is applied only when offshore employees are on stairs and it replaces the generic inclined-deck force term; the resulting force is applied along the defined local stair directions and then transformed to the global frame.

5.2.1. Evacuation Speed Settings

The normal walking and emergency evacuation speeds on stairs and flat surfaces are derived from IMO standards [24] and Zhang's experimental data [25], as summarized in Table 1. The values before the brackets represent the range of speeds reported in IMO standards or experimental studies, while the values within the brackets denote the mean values adopted in this study for simulation purposes. Based on the data in Table 1, the speed relationships under walking and running conditions are derived in Equations (16)–(19), which are used to describe speed relationships under walking and running conditions.

Table 1. Offshore employees speed under different working conditions [25].

Working Condition	Flat Surfaces/(m/s) (Mean)	Stair Climbing Speed/(m/s) (Mean)	Going Downstairs Speed/(m/s) (Mean)
Walking speed [24]	1.11~1.85 (1.48)	0.5~0.84 (0.67)	0.76~1.26 (1.01)
Running speed [25]	1.91~2.3 (2.11)	0.95~1.03 (1.0)	1.26~1.27 (1.26)

Normal walking speed (IMO, [24]):

$$v_{\text{Descent}} = 68\% \times v_{\text{flat}} \quad (16)$$

$$v_{\text{Ascent}} = 50\% \times v_{\text{flat}} \quad (17)$$

Running speed (Zhang et al., [25]):

$$v_{\text{Descent}} = 60\% \times v_{\text{flat}} \quad (18)$$

$$v_{\text{Ascent}} = 50\% \times v_{\text{flat}} \quad (19)$$

where v_{flat} denotes the evacuation speed of offshore employees on flat ground.

Since the offshore employees in this study are in the living quarters and evacuate from there to the muster station of the offshore platform, this paper primarily investigates the evacuation process of offshore employees going downstairs. Based on the mean speed data in Table 1, the speed of going downstairs was set to 1.0 m/s (walking condition) and 1.26 m/s (running condition).

5.2.2. Simulation Results

Fifty individuals were simulated under varying inclination angles at both walking and running conditions. As shown in Figure 11, the key findings are as follows:

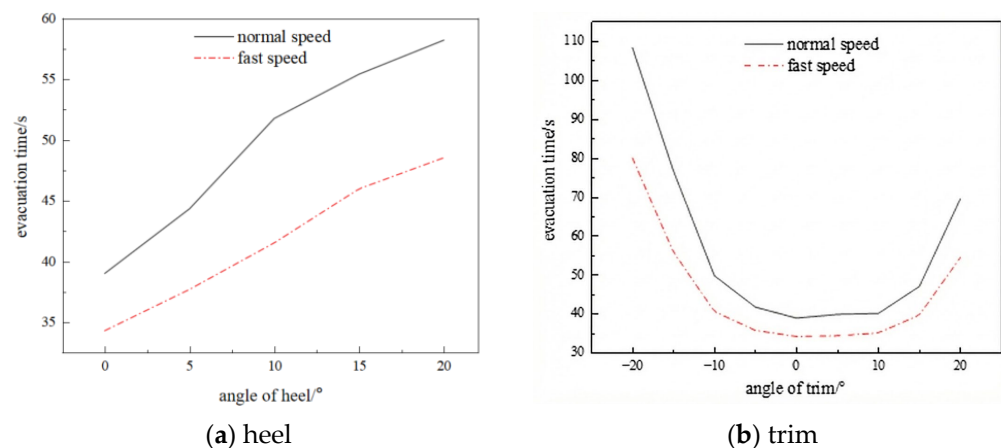


Figure 11. Stair evacuation results under (a) heel and (b) trim conditions.

1. Trimming by the bow produced the longest evacuation times due to the combined inclines of the platform and stairs.
2. Heel angle increases linearly extended evacuation times, reflecting greater lateral forces.
3. Trim angle $\leq 10^\circ$ had little effect, but evacuation time increased sharply beyond 15° .
4. Faster speeds reduced delays, improving evacuation times by 15–27% within $\pm 20^\circ$ inclination range.

These findings highlight the significant role of inclination in stair evacuation performance.

5.2.3. Speed Variation Modeling

Speed variations at different inclination angles were analyzed using the fitted equations (Equations (20) and (21)). Boxplots (Figure 12) illustrate speed variations under heel and trim conditions. In Figure 12, the central box represents the interquartile range (IQR), defined as the value between the 75th percentile Q3 and the 25th percentile Q1. The horizontal line within the box indicates the median. The whiskers extend to the furthest data points within the range of $[Q1 - 1.5 \text{ IQR}, Q3 + 1.5 \text{ IQR}]$. This 1.5 multiplier is a standard statistical threshold used to identify outliers; data points falling outside this calculated range are displayed as abnormal values. These outliers appear because some evacuees moved significantly faster or slower than most others, often due to local congestion, differences in initial positions, or balance adjustments when the walkway was inclined.

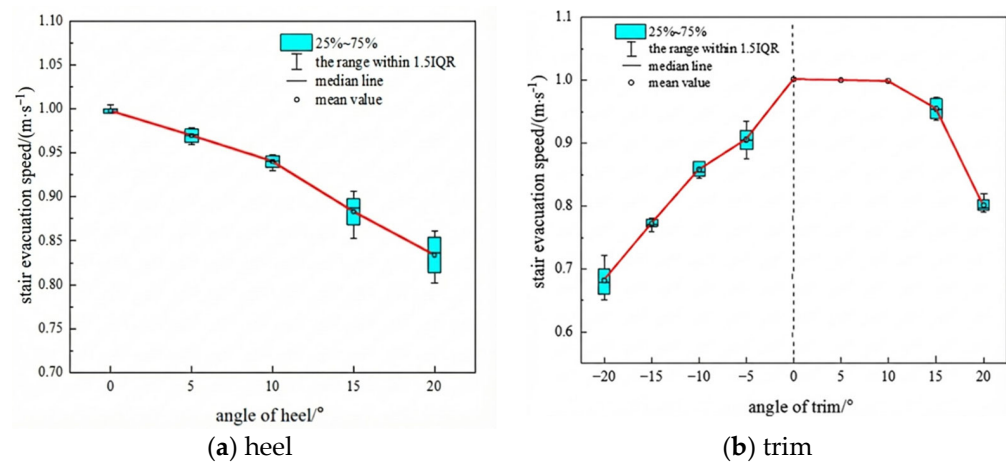


Figure 12. Evacuation speed on stairs under (a) heel and (b) trim.

Fifty individuals were analyzed to determine how evacuation time and speed vary with inclination angles. Key observations include the following:

1. When the heel angle is less than or equal to 10° , its effect on evacuation speed is minimal, resulting in only a slight decrease in movement speed.
2. For heel angle larger than 10° , the effect becomes more pronounced as evacuees must continually adjust balance.
3. Trim angle within 0 – 10° has little effect on evacuation speed.
4. Trim by the bow results in a clear decrease in evacuation speed due to the combined effects of inclination and stair slope.
5. Speed variability exhibits at larger inclination angles (15 – 20°), as shown by the box-plot analysis.

Based on the above variation in evacuation speed during the process of going downstairs, a two-segment piecewise linear regression was applied to the mean speed data obtained from the simulations (Figure 12). Using the Least Squares Method, linear functions were fitted within specific inclination angle intervals to minimize the deviation between the model and the simulation results. The resulting expressions describing the relationship between evacuation speed and inclination angle are given in Equations (20) and (21).

For stairs with heel angle (θ):

$$v = \begin{cases} -0.006\theta + 1.005 & 0^\circ \leq \theta \leq 10^\circ \\ -0.012\theta + 1.065 & 10^\circ < \theta \leq 20^\circ \end{cases} \quad (20)$$

For stairs with trim angle (ϕ):

$$v = \begin{cases} 0.02\phi + 1.07 & -20^\circ \leq \phi < -10^\circ \\ 0.013\phi + 1 & -10^\circ \leq \phi < 0^\circ \\ -0.0002\phi + 1 & 0^\circ \leq \phi < 10^\circ \\ -0.005\phi + 1.048 & 10^\circ \leq \phi < 15^\circ \\ -0.036\phi + 1.513 & 15^\circ \leq \phi \leq 20^\circ \end{cases} \quad (21)$$

To validate the proposed model, the fitted speed equations (Equations (20) and (21)) were benchmarked against datasets summarized in the HSVA (Hamburgische Schiffbau-Versuchsanstalt GmbH, Germany) report (<https://www.hsva.de/>) [24]. The comparison incorporates data from SHEBA (the EU Safety of Human Life in Evacuation and Behavior Analysis project), AENEAS (the evacuation modelling tool adopted by the IMO), and TNO (experimental results from the Netherlands Organization for Applied Scientific Research).

As shown in Figure 13, the speed-attenuation trends predicted by our model closely match these established standards, thereby confirming the model's reliability.

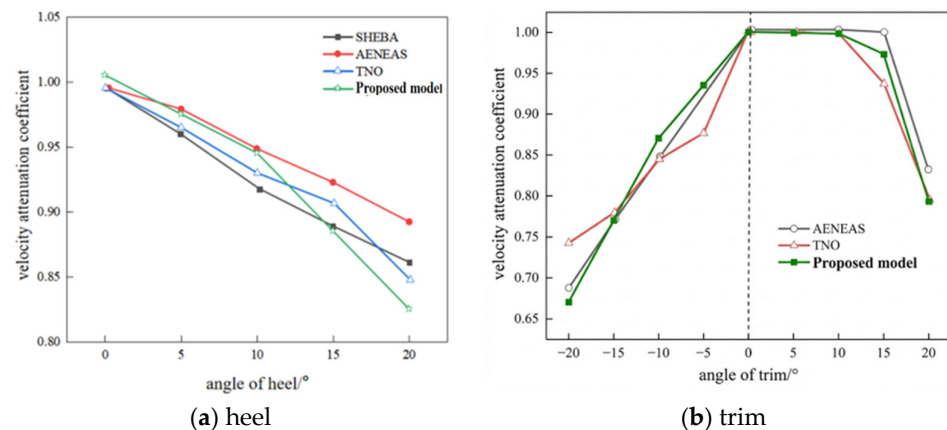


Figure 13. Comparison of evacuation speeds on stairs under various platform inclination angles.

5.3. Evacuation Simulation of Complex Living Quarters

5.3.1. Scenario Design and Parameters

Evacuation performance is also evaluated within the living quarters of an offshore platform (Figure 14). Heel angles ranged from 0° to 20° and trim angles from −20° to 20°. Following [10], only heel angles to port are considered, as no significant differences are found between heel angles to port and heel angles to starboard.

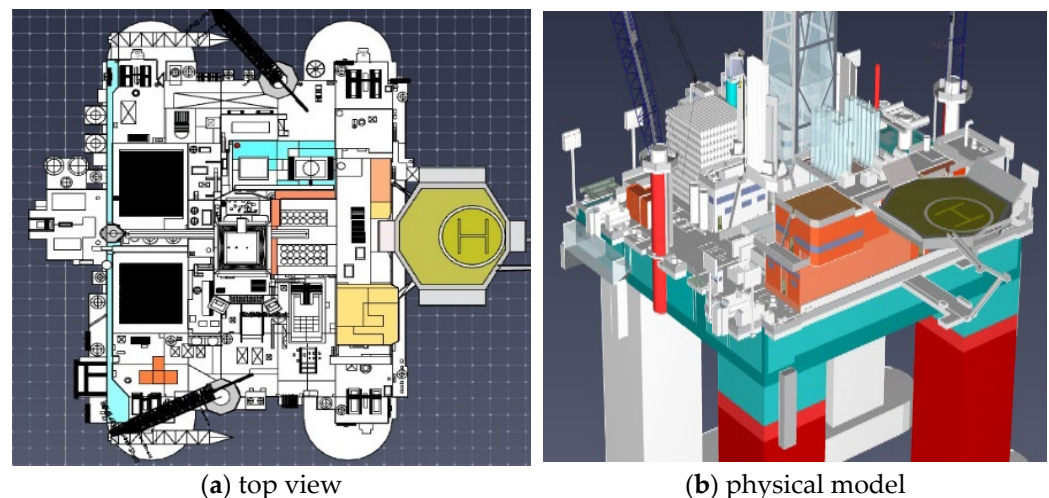


Figure 14. (a) Top view and (b) Physical model of the offshore platform.

Simulation parameters are defined as follows: response time constant $\tau = 0.5$, offshore employee radius r randomly distributed in the range $[0.25, 0.35]$ m, maximum speed $v_{\max} = 5$ m/s, mass $m = 75$ kg, and other key parameters listed in Table 2, which are based on experimental data in [10,26] and calibration against the IMO standards.

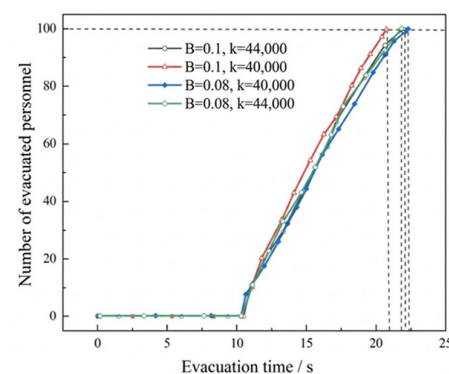
To assess the robustness of the simulation settings under inclined conditions, a targeted sensitivity analysis is performed for B and k , which directly affect contact interaction and congestion formation. The parameters A and κ are kept at their baseline values (Table 2) to reduce the number of parameter combinations. Four parameter combinations are evaluated:

- (1). $A = 2000$, $B = 0.08$, $k = 44,000$, $\kappa = 60,000$
- (2). $A = 2000$, $B = 0.08$, $k = 40,000$, $\kappa = 60,000$
- (3). $A = 2000$, $B = 0.1$, $k = 44,000$, $\kappa = 60,000$
- (4). $A = 2000$, $B = 0.1$, $k = 40,000$, $\kappa = 60,000$

Table 2. Simulation parameters for offshore employee dynamics.

Parameters	Symbol	Value
Human force strength	A_i	2000 N
The range of human force	B_i	0.1 m
Human elasticity coefficient	k	$40,000 \text{ kg}\cdot\text{s}^{-2}$
Coefficient of sliding friction	κ	$60,000 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$
Gravity acceleration	g	$10 \text{ m}\cdot\text{s}^{-2}$
Strength of attraction	C_{ij}	−2000 N
The range of attraction	D_{ij}	0.2 m
The exit attraction constant	G_{ie}	100 N

The results of the sensitivity analysis (Figure 15) indicate that the parameter set ($A = 2000$, $B = 0.1$, $k = 40,000$, and $\kappa = 60,000$) produces evacuation behavior that aligns well with the expected trends across all inclination angles. Although the curves exhibit similar smoothness without noticeable oscillations or abrupt jumps, this configuration offers two practical advantages: it maintains realistic interpersonal spacing throughout the evacuation process, and it yields the shortest overall simulation time in the comparative tests. Based on these combined considerations, this parameter set is selected for the subsequent simulations.

**Figure 15.** Parameter sensitivity analysis results.

Remark 2. A comprehensive sensitivity analysis of all parameters in Table 2 is beyond the scope of this study and will be addressed in future work.

Simulations are advanced using an explicit time-stepping scheme with a fixed time step $\Delta t = 0.01$ s. Offshore employee–offshore employee and offshore employee–obstacle interactions follow the repulsion + contact + tangential friction formulation; with friction activated only upon overlap. Obstacles and boundaries are treated as non-penetrable (“hard”) walls through these interaction forces. Individual parameters are set per scenario: v_{i0} is assigned according to the scenario and remains constant during each run, while τ is fixed. Randomness is introduced through initial positions (and radii if applicable), and each scenario is repeated with different random initializations.

5.3.2. Simulation Results of Evacuation Time

Evacuations with 30 and 40 offshore employees are simulated under both normal working conditions (uniformly distributed across two-decks in Figure 16) and resting conditions (offshore employees concentrated on single-deck in Figure 17). All evacuees are tasked with reaching lifeboat muster stations on both sides of the platform. Expected evacuation speeds are set to 1.2 m/s (walking), 1.6 m/s (fast walking), and 2.2 m/s (running) based on the IMO standards [24] and the experimental results of Zhang et al. [25]. How

these speeds influence evacuation efficiency under different platform inclination angles is analyzed in this section.

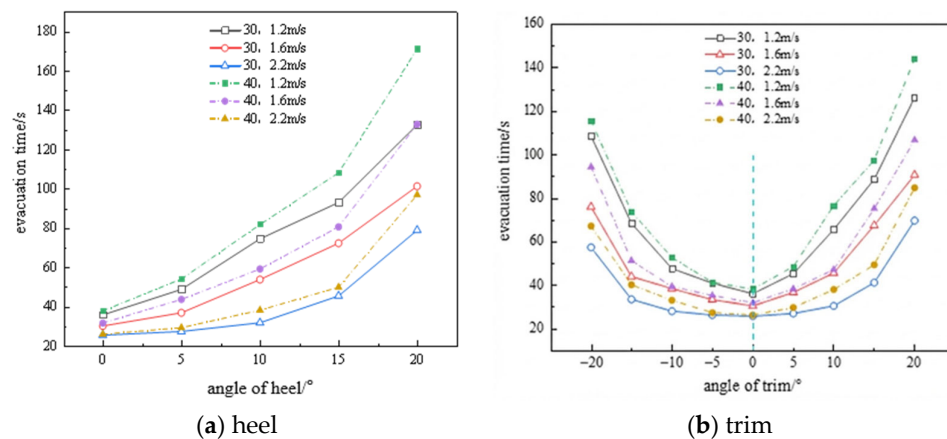


Figure 16. Evacuation time of offshore employees in living quarters under normal conditions.

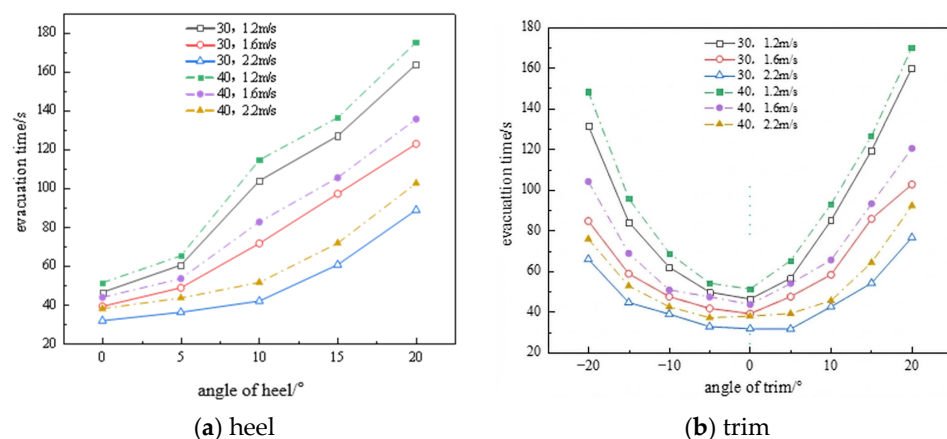


Figure 17. Evacuation time of offshore employees in living quarters under resting conditions.

Based on the above evacuation simulation time, evacuation under normal working conditions (two-decks uniform distribution) is compared with that under resting conditions (single-deck distribution) at different expected speeds as shown in Figure 18.

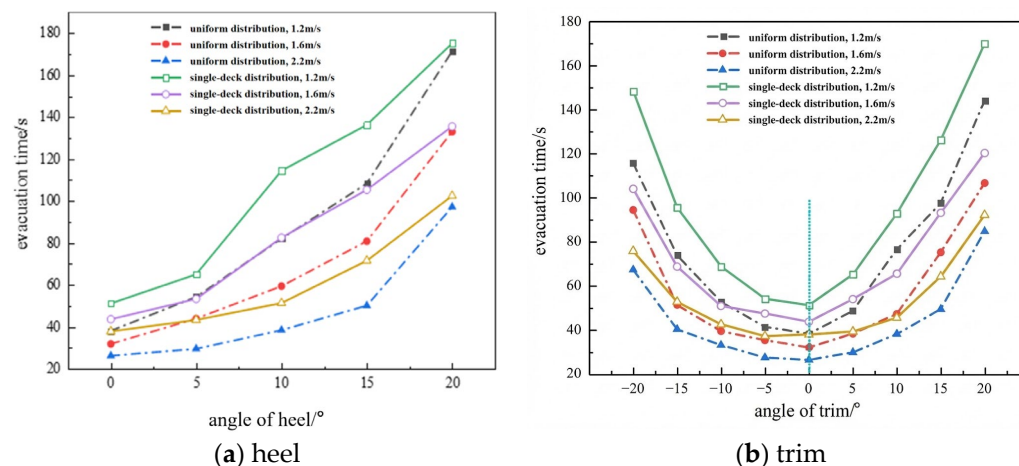


Figure 18. Evacuation time of offshore employees under different working conditions.

Key findings from Figures 16–18 can be summarized as follows:

1. Evacuation efficiency deteriorates as platform inclination increases. The impact is negligible below 5° , becomes noticeable between 5° and 15° , and accelerates significantly beyond 15° .
2. Evacuation efficiency decreases sharply once the heel angle exceeds 10° or the trim angle exceeds 15° . Heel angles primarily affect lateral balance and congestion at corners, while trim angles exert a stronger influence on stair use and inter-floor movement.
3. Resting conditions, where offshore employees are concentrated on a single deck, consistently lead to longer evacuation times due to higher density and congestion, and are more sensitive to platform inclination. By contrast, double-deck distributions improve flow separation and overall evacuation efficiency.
4. In single deck resting conditions, evacuation times exhibit relatively low variability across heel and trim angles. High density reduces individual behavioral differences.
5. Higher expected speeds (walking: 1.2 m/s, fast walking: 1.6 m/s, running: 2.2 m/s) substantially reduce evacuation times by about 15–27%, even under severe inclinations. However, for steep inclines and high desired speeds, these evacuation times should be considered optimistic lower-bound estimates, as the model does not explicitly account for slips, falls, injuries, incapacitation, or the secondary delays they may cause.
6. When stairways are involved, longitudinal trims directly alter the effective slope of steps, creating a disproportionately large impact on both stair climbing and going down stair speeds. This effect is more severe than that of heel conditions.
7. The observed thresholds and speed reductions are consistent with previous experimental and modeling studies [6,11,22], supporting the reliability of the model outcomes.

5.3.3. Speed Characteristics Analysis on Inclined Platform

To further investigate how inclination affects evacuation speed, a simulation involving 40 participants is conducted, with everyone's nominal movement speed set to 1.0 m/s. The objective is to analyze how heel and trim angles influence speed across a range of inclinations. Figure 19 presents the evacuation speed decay curves obtained from the simulation. Based on the simulation data, piecewise least-squares regression was performed on the mean normalized speed ratio $r(\theta) = v(\theta)/v(0)$ to derive compact surrogate expressions for practical use. Accordingly, Equations (22) and (23) represent regression fits to the simulation results, rather than direct empirical or biomechanical laws, and their coefficients are specific to the modeled environment, parameterization, and scenario settings [22].

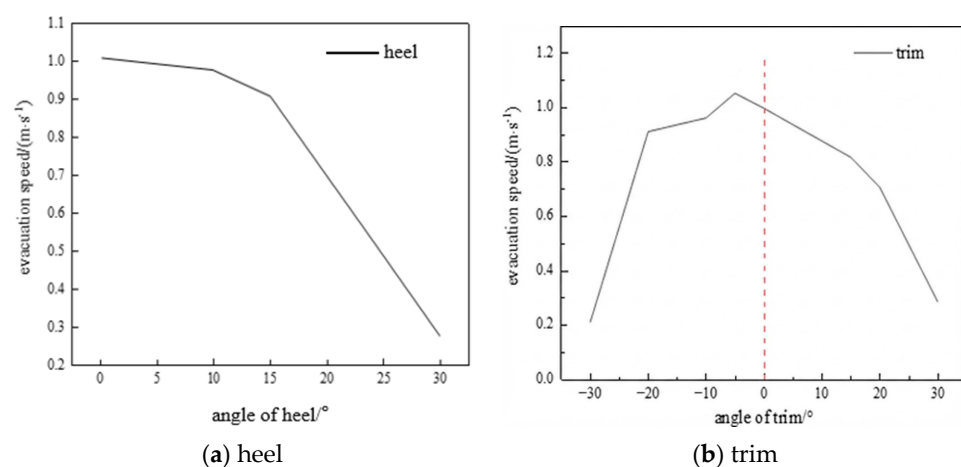


Figure 19. Evacuation speed under (a) heel and (b) trim conditions.

For heel angle (θ):

$$v = \begin{cases} -0.015\theta + 1.007, & 0^\circ \leq \theta < 20^\circ \\ -0.042\theta + 1.536, & 20^\circ \leq \theta \leq 30^\circ \end{cases} \quad (22)$$

For trim angle (ϕ):

$$v = \begin{cases} -0.012\phi + 0.996, & 0^\circ < \phi < 20^\circ \\ -0.042\phi + 1.546, & 20^\circ \leq \phi \leq 30^\circ \\ -0.0098\phi + 0.996, & -5^\circ < \phi \leq 0^\circ \\ 0.010\phi + 1.101, & -10^\circ < \phi \leq -5^\circ \\ 0.005\phi + 1.010, & -20^\circ < \phi \leq -10^\circ \\ 0.070\phi + 2.31, & -30^\circ \leq \phi \leq -20^\circ \end{cases} \quad (23)$$

The piecewise intervals were chosen to reflect the distinct regimes observed in Figure 19: speed changes are minimal at low inclinations (0° – 10°), a transition occurs around 10° – 15° , and speed decreases rapidly at higher inclinations ($\geq 15^\circ$). These break-points are consistent with the threshold behaviors discussed in this section and with commonly reported critical inclinations in benchmark datasets and prior studies.

The model's sensitivity to the adjustment forces is further assessed by repeating simulations under varying crowd densities, initial distributions, and inclination settings. Consistent with the trends reported by Fang et al. [9], the results indicate that when the inclination angle is below 15° , the self-adjustment force can partially offset the speed loss induced by the incline. Based on the above speed characteristics analysis, the following conclusions can be drawn.

1. Evacuation speed is only slightly affected when inclination is less than 10° , leading to negligible reductions in evacuation efficiency.
2. When heel angles exceed 15° , evacuation speed decreases markedly, as evacuees struggle to maintain balance and adapt to the slope.
3. At moderate inclinations, trim angles result in greater speed reductions compared to heel angles. At higher inclinations, increased swaying leads to more significant deceleration.
4. Trim by the bow initially increases movement speed, but larger trim angles cause speed deceleration as evacuees must slow down to prevent falls or collisions. This observation does not contradict the stairway case discussed earlier (Section 5.2.3), where trim by the bow always reduces speed because it combines with the stair slope to create a steeper effective gradient.

These findings emphasize the importance of incorporating inclination effects into evacuation planning and highlight the critical role of inclination in determining evacuation efficiency during offshore emergencies.

Due to the unique nature of the simulation scenarios, direct comparisons with previous studies are limited. To validate the results, the attenuation coefficients derived in this paper were benchmarked against external datasets, including the HSVA report as well as experimental findings reported by Sun et al. [6] and Fang et al. [11]. Figure 20 compares the evacuation speed curves obtained from the improved SFM ('Our result') with several internationally recognized benchmarks. These include the 'FTL & PSEG' dataset referenced in IMO validations, the AENEAS simulation tool, and experimental results from Monash University and KRISO. As shown in Figure 20 and quantified in Table 3 (heel angle) and Table 4 (trim angle), the speed–inclination trends predicted by the proposed model are in good agreement with independent datasets. The MAE, RMSE, and maximum deviations all fall within the reported ranges, supporting the validity of the approach.

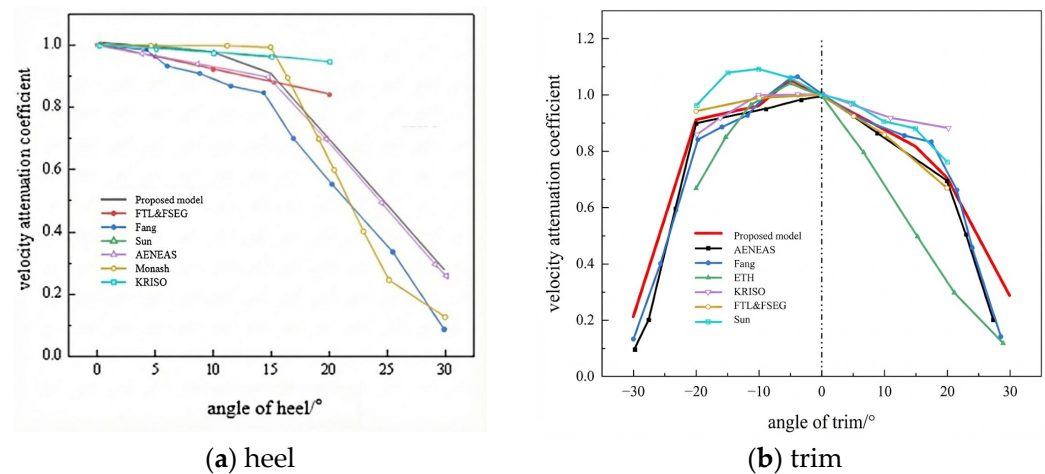


Figure 20. Comparison of evacuation speed from different studies under (a) heel and (b) trim condition.

Table 3. Angle of Heel Test: Comprehensive Comparison Table.

Comparative Dataset	Effective Range (°)	MAE	RMSE	Max Dev
AENEAS	0–30	0.021	0.027	0.050
Fang	0–30	0.096	0.114	0.119
Monash	0–20	0.083	0.116	0.240
KRIASH	0–20	0.015	0.019	0.025
FTL&FSEG	0–20	0.052	0.063	0.075

Table 4. Angle of Trim Test: Comprehensive Comparison Table.

Comparative Dataset	Effective Range (°)	MAE	RMSE	Max Dev
AENEAS	−30–30	0.050	0.068	0.150
Fang	−30–30	0.051	0.073	0.160
Sun	−20–20	0.058	0.076	0.130
ETH	−20–30	0.168	0.211	0.400
KRIASH	−20–20	0.053	0.074	0.180

As illustrated in Figure 20, the close agreement between our results and independent datasets is further confirmed by the error metrics in Tables 3 and 4 (MAE, RMSE, and Max Dev), reinforcing the reliability of the proposed model. The simulation outcomes reported in this study are consistent with previous research on evacuation under inclined conditions. For instance, Hu et al. [10] and Fang et al. [11] found that evacuation efficiency on passenger ships declines sharply once heel angles exceed 15°, aligning with our observation that evacuation times on offshore platforms increase markedly beyond this threshold. Similarly, studies of inclined building evacuations [23] have demonstrated the negative impact of slopes and uneven terrain on offshore employee speed and congestion. These parallels not only validate the present model but also underscore the unique evacuation challenges faced on offshore platforms compared with ships and buildings. Quantitative speed attenuation models were developed to capture the impact of platform inclination on evacuation speed. These results align with existing studies [10,11,23] and provide a practical reference for offshore evacuation planning.

6. Conclusions and Future Work

6.1. Conclusions

This study develops an improved SFM to simulate evacuation processes on offshore platforms under varying inclination conditions. The key conclusions are as follows:

- (1) By integrating inclination-induced forces with attraction forces, the improved SFM is better equipped to simulate evacuation on tilted platforms. The simulation results corroborate the model's validity and reliability for scenarios involving platform inclinations.
- (2) Evacuation time increases with the steepness of inclination. When the inclination angle exceeds 15° , platform inclination leads to a 20–50% increase in predicted evacuation duration. Timely evacuation before this threshold is therefore critical to prevent capsizing risks and casualties.
- (3) Longitudinal trim exerts a greater influence than lateral heels because stairways are usually aligned with the platform's longitudinal axis. Trim directly increases the effective slope of stair treads, increasing gravitational resistance during stair climbing and slip risk while going downstairs. Heel primarily causes lateral imbalance, which evacuees can partially mitigate by using handrails or leaning against walls. As a result, longitudinal trims produce more severe delays than lateral heels of comparable magnitude do.
- (4) In complex living quarters, evacuation efficiency is strongly affected by population density and spatial distribution. Resting conditions, where offshore employees are concentrated on a single deck, consistently lead to longer evacuation times and higher sensitivity to inclination compared with working conditions.
- (5) The study identifies 15° as a conservative critical threshold for safe evacuation. This finding supports the development of platform-specific evacuation guidelines and highlights the need for design strategies that minimize stair bottlenecks, reduce single-deck crowding, and provide accessible muster routes.

6.2. Future Works

While the improved SFM offers significant advances, several limitations remain. The current model does not fully capture panic behaviors, psychological stress, or heterogeneous individual responses under inclined conditions. To further enhance realism and applicability, it is worth carrying out future work as follows:

1. Extending the model to account for panic propagation, group cohesion, and heterogeneous behavioral thresholds during evacuation.
2. Investigating the combined impacts of fire, explosion, and platform inclination to provide more comprehensive risk assessments under multi-hazard scenarios.
3. Calibrating and validating the model with data from offshore evacuation drills and real incidents to strengthen its practical relevance with empirical validation.
4. Incorporating behaviors such as handrail usage, crawling, or adaptive movement strategies under severe inclinations to improve simulation accuracy.

By addressing these aspects, future research can further advance evacuation modeling, enabling more robust and reliable evacuation planning for offshore platforms.

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