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Evacuation Performance on Offshore Platforms Considering the Effect of Visibility

Wang T., Wang Y., Li YX., Wang J.

Abstract

On offshore platforms, low visibility may occur at night, in foggy weather, or in fire incidents. However, little attention has been focused on the evacuation affected by the low visibility conditions on offshore platforms. Therefore, different visibility cases are designed including normal visibility and restricted visibility conditions with visibility distance of 10 m, 5 m and 1 m. Fire accidents are also considered to study the effect of restricted visibility caused by smoke on the evacuation of personnel. Besides, walking and running modes are involved in each case. The total evacuation time index (*ETI*), queuing time index (*QTI*), increment rate of the *ETI* (ω_{ETI}) and *QTI* (ω_{QTI}) are analyzed. As a result of analysis, *ETI* will increase as visibility becomes worse, and it can change significantly as visibility drops from 5 m to 1 m. Queuing mainly occurs in the living area, and *QTI* increases as visibility becomes worse or personnel evacuate with a slower speed. "Long tail effect" is observed in the evacuation process, while the evacuation time for the last 10% evacuees can be pretty long. Based on the evacuation conditions in the Deepwater Horizon accident, measures are taken to reduce the long tail effect. The total evacuation time can be reduced consequently. This study can provide useful insights for the evacuation of personnel on offshore platforms under restricted visibility conditions.

Keywords: Offshore platform; Restricted visibility; Evacuation time; Queuing; Long tail effect

1. Introduction

An explosion and fire on the Piper Alpha platform occurred about 10 pm on the 6th of July, 1988. In the accident, 167 people were killed, huge explosion and fire destroyed the platform. The accident is the world's most serious offshore platform accident [1]. Another serious accident, the Deepwater Horizon blowout accident, happened around a quarter to 10 pm on the 20th of April 2010, the accident took away 11 lives and caused serious environmental pollution [2]. Both accidents occurred at night, which means that the personnel on both platforms had to complete their evacuation at night. Therefore, when studying the evacuation during an offshore platform accident, it is not only necessary to consider the impact of the accident itself, but also the effect of the natural environment.

Low visibility situations can result from smoke spread in fire accidents, lighting failure due to the accident or adverse natural environment, such as foggy weather. Since the low visibility can reduce the evacuation speed, increase the evacuation time, and increase the risk of being exposed to accidental hazards, it is regarded as an indirect but fatal cause of death [3]. Studies of the effects of visibility conditions on common buildings evacuation continues to increase, and the research methods can be mainly divided into two categories: experimental research and simulation research. Jin [4] conducted an evacuation experiment in a smoke-filled 20-m long corridor to investigate the influence of visibility on walking speeds. The smoke was generated by burning wood (irritant) or kerosene (non-irritant). However, the experiments only involved a small range of extinction coefficient (0-1/m). Based on Jin's experiments, Frantzich and Nilsson [5] and Fridolf [6] carried out similar experiments, except that they designed a wider range of smoke extinction coefficient. Frantzich and Nilsson used artificial smoke and added gaseous acetic acid to create an irritating smoke environment with the extinction coefficient ranges from 2 to 8/m, and the function of guide lights in tunnel fires was considered [5]. Fridolf also designed and used artificial smoke and acetic acid to carry out evacuation experiments with extinction coefficients ranging from 1 to 4/m in a 200 m long railway tunnel to study the evacuation behavior of personnel [6].

The data and methods of the above experiments were often used by researchers. Besides, the studies of evacuation in restricted visibility have been extended to a wider range of buildings. The experimental method has also been innovated. Jeon [7, 8] innovatively used eye masks with different transparency to simulate the effect of smoke. He carried a series of experiments in a 4th-floor subway station to study the evacuation behaviors in different visibility conditions. Since applying different transparency eye masks to simulate different visibility conditions has many advantages, such as harmlessness and reusability, the method has been adopted by many researchers. For example, in Cao's experiment [9], plastic goggles with a light transmittance of about 0.3% were used to study the evacuation of personnel in a supermarket under limited visibility and the typical behavior during the evacuation process. Seike [10] simulated a completely darkened tunnel by wearing tape-sealed blindfolds (zero visibility) for the evacuees, so as to study the evacuation speed and evacuation behavior of personnel for different age ranges and genders. Opaque kerchief was used to create limited visibility conditions in Xue's experimental research [11], and the use of monetary incentive to mimic different emergency levels and the resulting effects in the evacuation process with limited vision were investigated. A similar method was also applied to study the evacuation of personnel in stairwells under restricted visibility, including the typical behaviors and speed on the ascending and descending stairs [12, 13].

Compared with experiments, computer simulation has also been widely used to simulate evacuation due to its unique advantages such as repeatability and lower cost. Evacuation models, including a social force model (SFM) and a cellular automata model (CAM), are often used to study the evacuation of personnel under restricted visibility. Wang [14] proposed three different evacuation strategies and investigated the performances of these strategies under limited visibility through a revised SFM. CAM was applied by Yuan [15] to simulate evacuations from a large smoke-filled compartment, and the evacuation behaviors considering the visibility range were modeled. The above studies were focused on the evacuation behavior under restricted visibility, however, they assumed that the restricted visibility had no effect on the evacuation speed. Obviously this assumption is not realistic, knowing that the restricted visibility can result in reduced evacuation speed, and eventually affects the evacuation time [4-6]. In contract, based on experimental data, some fire-evacuation simulation software considers the effect of restricted visibility on the evacuation speed. For example, the fitting equation of the evacuation speed with the extinction coefficient used in FDS+EVAC [16] is based on the experimental data of Frantzich and Nilsson [5]. The mobility of personnel under the influence of smoke in EXODUS [17] is based on Jin's [4] experimental data. Both FDS+EVAC and EXODUS have also been widely used to consider the effect of visibility on the evacuation of personnel [18, 19].

Different from ordinary buildings, offshore platforms are more susceptible to the natural environment, like foggy weather. Besides, they are prone to fire or explosion accidents, and the evacuation performance on the platform is also easily affected by the adverse environment. It means that personnel on platforms may have to evacuate under restricted visibility. However, limited research is focused on the evacuation on offshore platforms considering the restricted visibility. Zhang [20] conducted evacuation experiments on an offshore platform under smoke situations, and the evacuation performance of personnel was analyzed, including the evacuation time, evacuation speed, typical behavior and route choice. This experiment is significant, because it offers valuable evacuation data, which is helpful for studying the evacuation performance under fire on offshore platforms. However, only four decks were used in the experiments. Besides, the low visibility does not involve the outdoor area of the platform. To overcome the above deficiencies, a series of evacuation simulation studies will be conducted under different visibility conditions on a selected offshore platform.

The rest of this paper is organized as follows. Section 2 mainly introduces the improvements and verification of the evacuation speed model, different cases are also described in this section. The results of the simulation cases under different visibility conditions are compared, and parameters of the evacuation, including the evacuation time and queening time during evacuation process are analyzed in Section 3. Section 4 mainly presents the conclusions and future work.

2. Methodology and Objects

2.1 The offshore facility layout and personnel distribution

FDS + EVAC is used for modelling the evacuation process considering the effect of visibility on an offshore platform. The selected offshore platform has four decks, namely the helicopter deck, the upper deck, the lower deck and the working deck. The upper deck, lower deck and working deck mainly include control rooms, engine rooms, essential equipment and systems for the drilling process. The living building is located at the east side of the upper deck, and two lifeboats are suspended overboard at the east side of the living building. The helicopter deck is located at the top of the living building. The main geometric structures are shown in Fig.1.

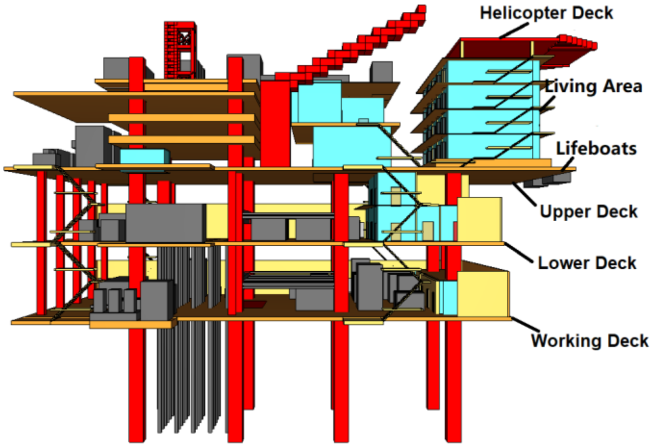


Fig.1 Geometric structure of the selected offshore platform

According to the actual personnel data of the selected platform, normally 120 workers work on the platform and all of them are males. The workers are randomly located on different decks. In this research, it is assumed that all workers are familiar with the location of the exits and assembly station. The shoulder width of the personnel is obtained based on the "Human Dimensions of Chinese Adults" [21]. Detailed distribution and features of the personnel are shown in Table 1.

Table 1 Distribution and features of the personnel

Deck	Number of personnel	Response time (s)	Shoulder Width (m)
Living Area on the 1st Floor	20		
Living Area on the 2nd Floor	15		
Living Area on the 3rd Floor	15		
Living Area on the 4th Floor	10	N(90,30)[19]	0.427[21]
Upper Deck	17		
Lower Deck	20		
Working Deck	23		

2.2 **Modified evacuation speed model**

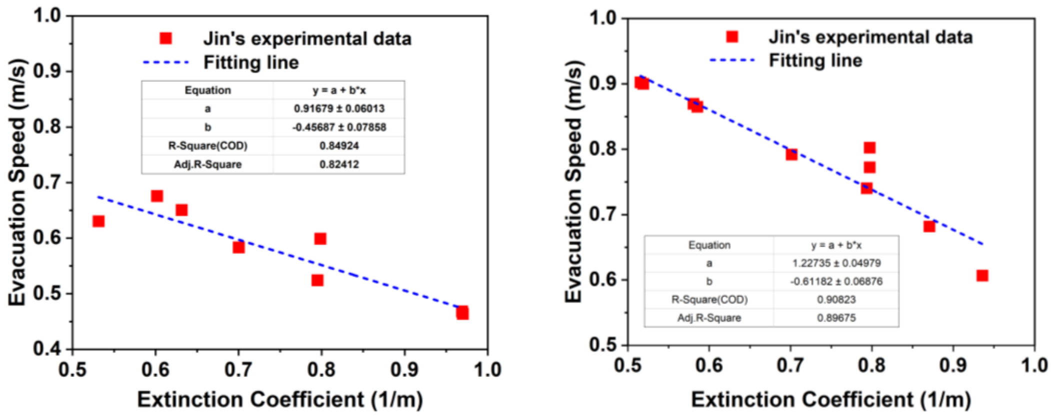
In the numerical simulation work, FDS + EVAC is selected because it considers the effect of smoke on the evacuation speed. The effect mechanism is shown in Eq. (1).

$$v_i^0(K_s) = Max\left\{v_{i,min}^0, v_i^0\left(1+\frac{\beta}{\alpha}K_s\right)\right\} \quad (1)$$

where $v_i^0(K_s)$ represents the evacuation speed of agent i in smoke, the minimum walking speed of agent i is $v_{i,min}^0 = 0.1 \cdot v_i^0$, v_i^0 (m/s) is the evacuation speed of agent i in normal condition. The values of the coefficients α and β are $0.706 m \cdot s^{-1}$ and $-0.057 m^2 \cdot s^{-1}$, respectively [16]. The impact factor (represented by $\gamma, \gamma = \frac{\beta}{\alpha}$), of the extinction coefficient on evacuation speed is calculated as -0.08. K_s is the extinction coefficient, while in FDS+EVAC, the visibility S (m) is converted from the predicted light extinction coefficient K_s (1/m) using a constant C, assumed to be 3 for light-reflecting signs [16].

$$S = C/K \tag{2}$$

The fitting Eq. (1) of the evacuation speed that is embedded in FDS+EVAC software is developed based on Frantzich and Nilsson's experimental data [5]. The extinction coefficient involved in Frantzich and Nilsson's experimental research ranges from 2 to 8/m [5]. However, whether Frantzich and Nilsson's experimental data can be used to accurately predict the evacuation speed with K_s in the range of 0 to 1/m remains to be verified. Here, the data are fitted between walking speed and extinction coefficient of Jin's non-irritating smoke experiment [4], the minimum and maximum slope were obtained, with the fitting line as shown in Fig.2.



(a) Minimum slope (a) Maximum slope

Fig.2 Fitting of Jin's experimental data

From Fig.2, the slope represents the impact factor γ of the extinction coefficient (0~1/m) on evacuation speed. The impact factor γ_{Jin} ranges from -0.61 to -0.46 in Jin's experiment while $\gamma_{F\&N}$ is calculated as -0.08 for Frantzich and Nilsson's. Obviously the impact factors obtained from these two experiments have a large gap. Here the maximum value of γ_{Jin} was selected as the impact factor of the extinction coefficient on the moving speed due to the following two reasons. Firstly, the data in Fig.2 is based on Jin's non-irritating smoke experiment. However, some combustions may release irritating gases, such as HCl and HCN [22]. Jin's research shows that irritating gases can cause physiological discomfort, such as running tears, which will further reduce the evacuation speed of personnel in smoke [4]. Secondly, the evacuation routes with obstructions can also have a negative impact on evacuation [23, 24], which is not considered in Jin's experiment. However, obstructions as shown in Fig.3 exist on offshore platforms, they can also affect the evacuation speed. Consequently, considering the above reasons, γ_{Jin}= -0.61 is selected while K_s ranges from 0 to 1/m. As K_s increases to more than 1/m, $\gamma_{F\&N}$= -0.08 is then applied. Besides, Seike [10] has pointed that the evacuation speed will be extremely slow in completely darkened situations. Hence, as the extinction coefficient reaches a certain value (K_s=9.29m^{-1}), evacuees will move at the speed of $0.1v_i^0$ [16]. In summary, the evacuation speed model under the effect of visibility is modified as Eq. (3).

$$v_i^0(K_s) = \begin{cases} v_i^0(1-0.61K_s), & K_s \le 1m^{-1} \\ 0.39v_i^0(1-0.08K_s), & 1m^{-1} < K_s \le 9.29m^{-1} \\ 0.1v_i^0, & K_s > 9.29m^{-1} \end{cases} \tag{3}$$

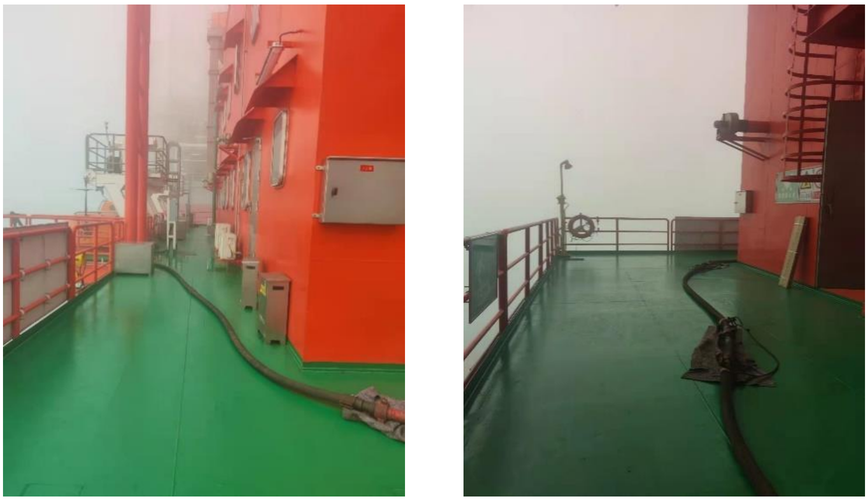


Fig.3 Obstructions in corridors on an offshore platform

The evacuation speed v_i^0 is determined based on Zhang's experimental research [20]. In their research, the speed of running in corridor was between 1.91 m/s and 2.3 m/s under normal visibility, while the speed in walking mode was measured with 1.65 m/s. In our research, both the running mode and walking mode are considered. The evacuation speed considering the extinction coefficient is shown in Fig.4. It is assumed that when the extinction coefficient reaches a certain value (K_s=9.29m^{-1}), personnel continue to move with a very slow speed [16]. The minimum evacuation speed in running mode is 0.23 m/s, and the value in walking mode is 0.165 m/s.

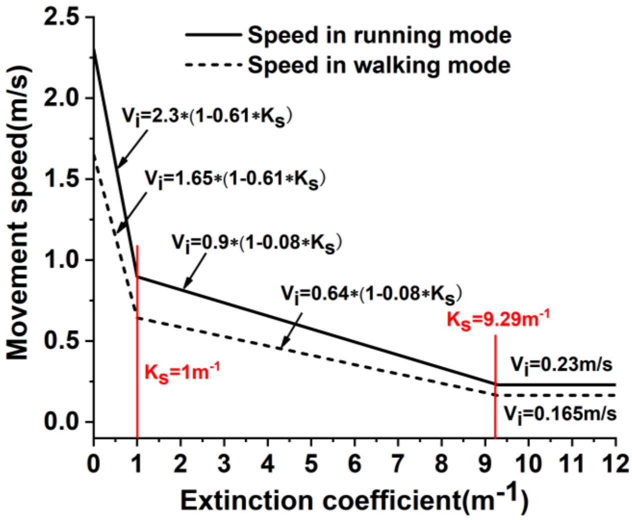
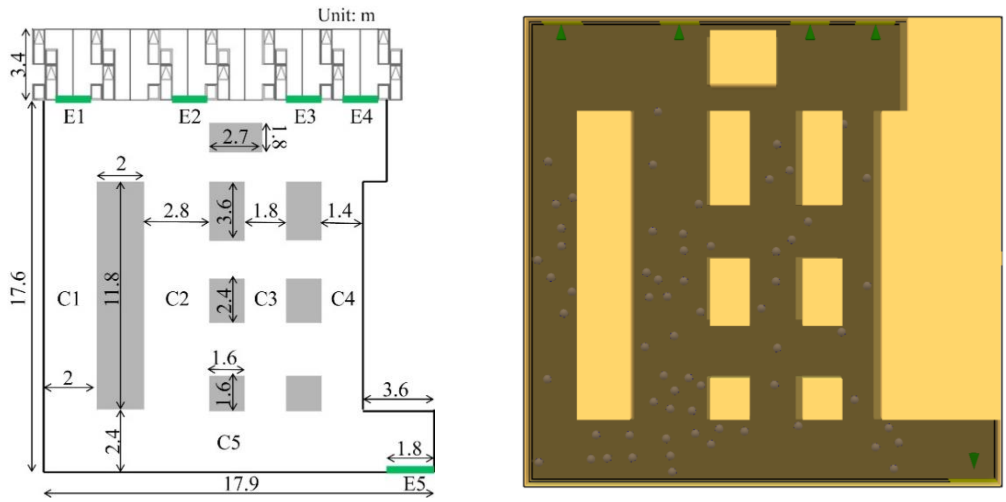


Fig.4 Evacuation speed versus extinction coefficient in different evacuation modes

2.3 Verification of the modified evacuation speed model

Cao's [9] evacuation experiment under restricted visibility was used to verify the modified evacuation speed model, because the detailed building layout and experimental analysis were provided in his research. In order to verify the modified evacuation speed model, the simulation results of the modified model are compared with Cao's experimental results. The detailed building layout and the physical model built by FDS+EVAC software are shown in Fig.5 (a) and (b).



(a) building layout from reference [9]   (b) physical model built by EVAC

Fig.5 Layout of the selected building

In Cao's experiment [9], sixty five people with normal eyesight distributed uniformly in corridors C1-C5 as shown in Fig.5 (a), and people could move to exits E1-E5 to complete the evacuation. The restricted visibility was realized by wearing a plastic glass, and the visibility was estimated to be 5 m. The experiment was carried including people evacuating under normal visibility and restricted visibility. The walking speed under normal visibility was measured of 1.2±0.19 m/s, which was used as the input for the normal walking speed of the personnel in the modified evacuation speed model. Two cases were used. In one case, exits E1-E4 were open while E5 was closed. In the other case, exits E1-E5 were all opened. The simulation was repeated ten times for both cases.

The comparison of the simulation and experimental results is shown in Table 2. The EVAC model can be used to predict the evacuation time of personnel under good visibility. The error rates of Case 1 and Case 2 are both within 5%. However, under restricted visibility, the simulation results using the original EVAC model have the error rates of 23.3% and 22% compared with the experiments. The effect of visibility on evacuation was underestimated obviously in both cases. Then the modified evacuation speed model was used in Case 5 and Case 6. From Table 2, it can be seen that the modified EVAC model could be used to predict the evacuation time with the error rates of 7.9% and 3.7% for Case 5 and 6. Through the validation, it can be achieved that the modified EVAC model can be used to provide accurate prediction of personnel evacuation time both under normal and restricted visibility conditions.

Table 2 Comparison of the simulation and experimental results

Experiment	Case	Available exits	Experiment time (s)	Simulation times (s)	Error rate
Good	1	E1-E4	24	23.5±1.0	2.1%
visibility	2	E1-E5	22	21±1.4	4.5%
Restricted	3	E1-E4	33	25.3±0.4	23.3%
visibility	4	E1-E5	30	23.4±1.7	22.0%

	5	E1-E4	33	35.6±1.1	7.9%
	6	E1-E5	30	31.1±1.4	3.7%

2.4 **Case descriptions**

The marine environment is complex and changeable, accidents such as fire and explosion are prone to occur on offshore platforms. The evacuation in these conditions is different from normal condition. Therefore, numerical simulations are conducted to study the effects of different visibility conditions on personnel evacuation. As shown in Fig.6, the cases are mainly divided into three groups. In Case A, normal visibility is considered and the visibility is above 10 m. The constant restricted visibility with the visibility distance of 1 m, 5 m and 10 m are designed in Case B, considering the evacuation in foggy weather or night. A fire accident is designed in Case C to study the effect of intermitted restricted visibility on personnel evacuation. Detailed descriptions of each case are shown in Table 3.

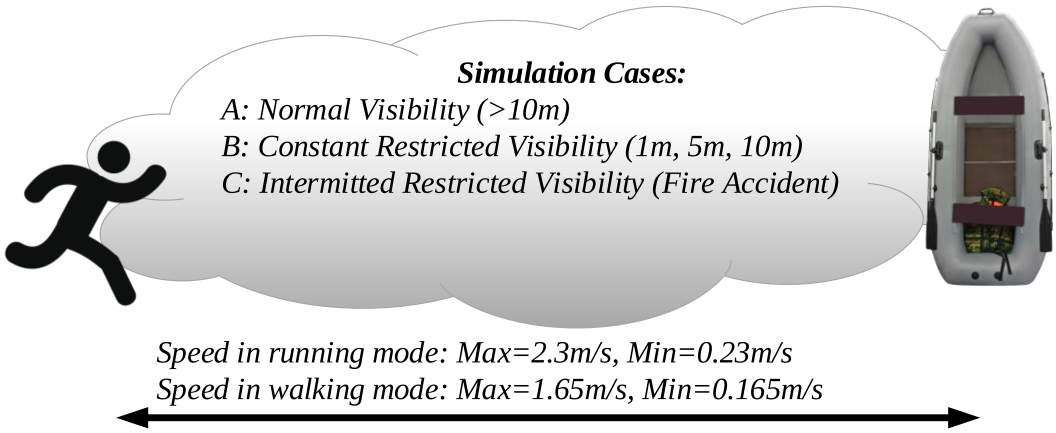


Fig.6 Graphic of the overall cases of the simulation works

Table 3 Detailed descriptions of each case

Case		Evacuation mode	Visibility condition
A	A1	Walking	Normal
	A2	Running	Normal
B	B1	Walking	10 m
	B2	Running	10 m
	B3	Walking	5 m
	B4	Running	5 m
	B5	Walking	1 m
	B6	Running	1 m
C	C1	Walking	Fire accident
	C2	Running	Fire accident

2.5 **Index for the safety analysis of evacuation**

The terms “Evacuation”, “Escape” and “Rescue” (EER) play a vital role in safeguarding the lives on offshore platforms [2, 25]. Evacuation means that personnel leave the dangerous area of the platform without directly entering the sea. The evacuation process is one of the most significant aspect that should be considered when evaluating the safety management of offshore platforms [26].

In this research, the effect of different visibility conditions on the evacuation of evacuees is studied. The evacuation time index (ETI) is utilized to evaluate the efficiency of the whole evacuation process. ETI can be divided into the evacuation time index in the working area ($ETI_{working}$) and the evacuation time index in the living area (ETI_{living}). Both $ETI_{working}$ and ETI_{living} can be obtained from the simulation results of FDS + EVAC based on Eq. (3).

$$ETI = T_{pre} + T_{tra} = T_{det} + T_{res} + T_{tra} \tag{3}$$

where T_{det} is the detection time, which is not considered in the research. T_{res} refers to the response time and it follows the normal distribution as shown in Table 1 [19, 27]. Both T_{det} and T_{res} are called the pre-evacuation time T_{pre}. T_{tra} is the travel time. In the research, T_{tra} involves the time required in both walking mode and running mode.

Since the exits of the offshore platform are narrow, once the arrival rate of evacuees is larger than the maximum flow rate the exit can handle, the evacuees will queue up until there is room to move forward [19, 20]. Queuing time index ($QTI_{working}$ and QTI_{living}) is then proposed to quantify the effect of queuing on the evacuation in the working or living area. Obviously waiting or slow walking occurs repeatedly during the evacuation process, which can be regarded as queuing. QTI can be obtained from Eq. (4).

$$QTI = \frac{\sum_{j=1}^{n} T_{que,j}}{ETI} \times 100\% \tag{4}$$

where $T_{que,j}$ is the queuing time (s) in the jth queuing area. QTI can reflect the impact of queuing on the evacuation. The larger the value of QTI, the lower the evacuation efficiency. Such congested situations may not only increase the evacuation time but also cause injury among evacuees [26].

To understand the increment of the ETI and QTI caused by low visibility, the change rate ω is calculated using Eq.(5).

$$\omega(m, r) = \frac{x(m, r)}{x_{normal-m}} \tag{5}$$

where ω represents the change rate of evacuees' evacuation index under restricted visibility compared to normal visibility. Furthermore, m is the evacuation mode, including walking and running while r is the restricted visibility, involving the constant restricted visibility and the intermitted restricted visibility. Therefore, $\omega(m, r)$ is the change rate of the evacuation index for a certain evacuation mode under restricted visibility conditions, and $x(m, r)$ is the evacuation index for a certain evacuation mode and restricted visibility conditions. Finally, $x_{normal-m}$ is the evacuation index for a certain evacuation mode under normal visibility conditions.

3. Simulation results and discussions

In this section, the influences of different restricted visibility on evacuation time index, queuing time index and the change rate of evacuees' evacuation indexes are analyzed. Comparisons of the evacuation performance between different cases are carried out. Besides, measures to improve the evacuation efficiency on offshore platforms are given at the end of this section.

3.1 Evacuation performance under normal visibility

Evacuation drills on offshore platforms are important, and most of the evacuation drills are carried out under normal conditions, and the impact of accidents on evacuation is not considered. In addition, some evacuation studies are also conducted in a calm situation [19]. In this aspect, a number of evacuation simulation is carried out under normal conditions firstly as the controlled experiments. Table 4 shows the simulation results of Case A.

Table 4 Simulation results of Case A

Case	$ETI_{working}$ (s)	ETI_{living} (s)	T_{que} (s)	QTI_{living}
A1	230.4±6.0	168.3±4.6	44.4±3.6	26.4%
A2	196.6±3.3	151.4±4.1	35.5±5.0	23.4%

For Case A1, the speed of 1.65 m/s [20] was applied as the input in the walking mode. Also, the speed was validated, matching well with the value of speed given by the IMO, which recommends that the walking speed of male crews should be in the range of 1.11–1.85 m/s [28]. The simulation results show that evacuees on the working deck have a longer evacuation distance and require longer evacuation time than those on other decks do. Therefore, *ETI* is equal to $ETI_{working}$, which is 230.4s for Case A1. Queuing or congestion may occur as evacuees choose their familiar path and gather at a certain exit [9, 26], or encounter the counter-flow crowd [20]. In this research, queuing mainly occurs at the first floor of the living area. As shown in Fig.7, evacuees at the first floor of the living area evacuate along the routes with green arrows. They have to pass through Area 1 or 2, and use Stairs 1 and 2 to reach the location of lifeboats. In Case A1, evacuees from the upper floors arrive at Areas 1 and 2 through Stairs 3 and 4 around 108s. As the evacuees from upper floors encounter with those from the first floor in Area 1 and 2, queuing occurs. The queuing time lasts for appropriately 44.4s, and accounts for 26.4% of the evacuation time in the living area.

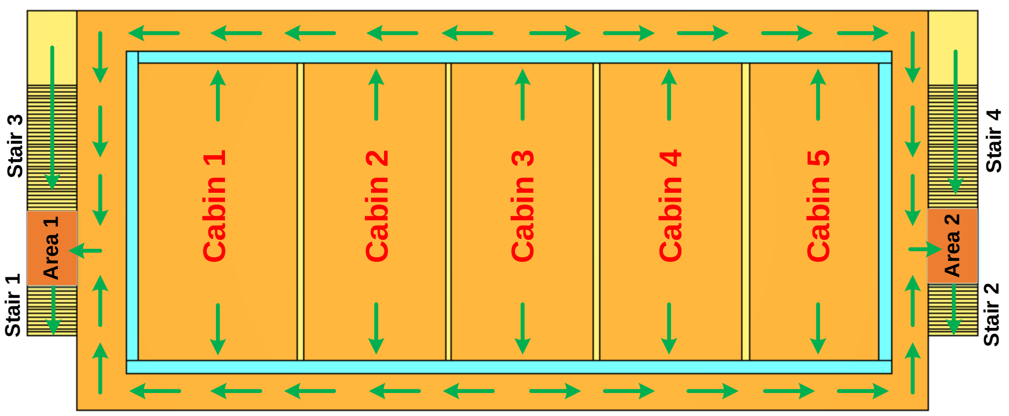


Fig.7 Evacuation routes at the first floor in the living area

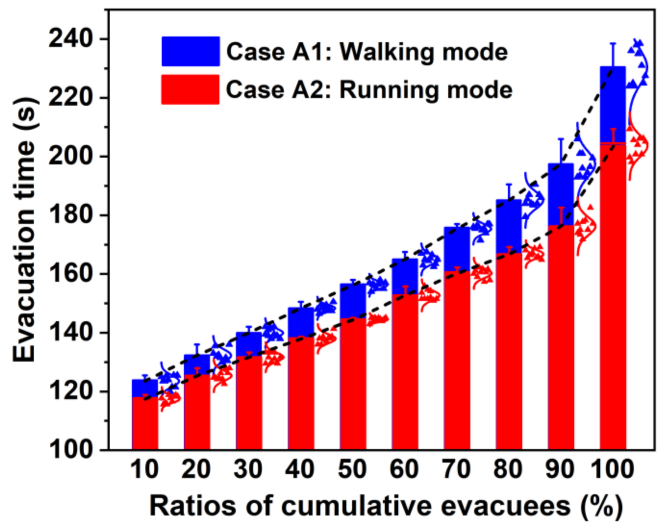
However, the threat of imminent danger could make evacuees walk faster or even run depending on the situation, instead of walking normally [29]. It is therefore essential to consider the running evacuation mode. The total evacuation time for running mode is 196.6s, it is shortened by 33.8s compared with Case A1. The increased evacuation speed has caused the queuing to occur in Areas 1 and 2 for 103.7s. However, the queuing time lasted for 35.5s, which is shorter than the one in Case A1, and QTI_{living} in Case A2 is reduced by 3.0% compared to Case A1.

Fig.8 (a) shows the distribution of the evacuation time required for different ratios of cumulative evacuees. It is found that in both cases, the evacuation process can be roughly divided into two phases. In the first phase, the evacuation time for every 10% increase ratio of evacuees shows a similar trend. However in the second phase, the evacuation time for the last 10% evacuees is significantly increased. The phenomenon is described as "long tail effect", that during the evacuation process, a few evacuees have longer evacuation time than others because of being informed later, poor action, or choosing a longer path in a certain complexity of the building [30]. This phenomenon will affect the overall evacuation time.

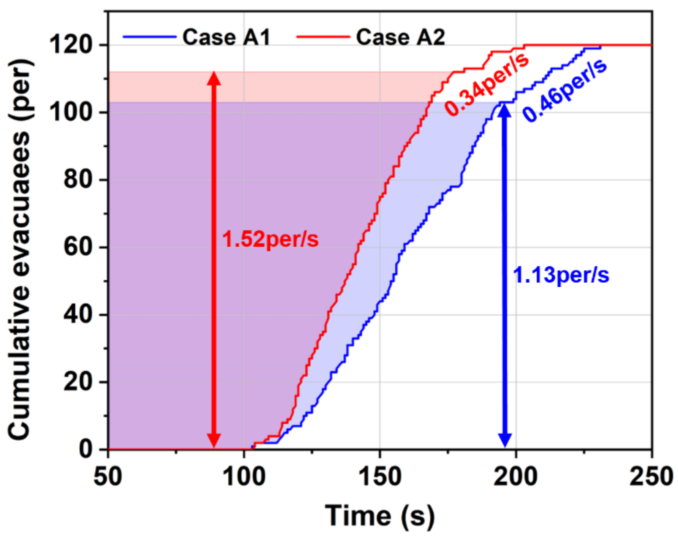
To analyze the evacuation efficiency during different phases of the evacuation process, the evacuation rate φ is determined using Eq.(6).

$$\varphi = \frac{\sum p}{t_2 - t_1} \tag{6}$$

where $\sum p$ represents the cumulative evacuated personnel, t_1 and t_2 are the starting and ending time of each phase. Fig.8 (b) compares the evacuation rates of the two phases between Cases A1 and A2. In phase one, there is no significant difference at the beginning between two cases, where evacuees near the lifeboats firstly complete the evacuation around 103s. However, as more and more evacuees complete the evacuation, the time gaps between two cases are gradually increasing. This can also be observed in Fig.8 (a). The evacuation rates for Cases A1 and A2 are calculated as 1.13 per/s and 1.52 per/s in phase one. After approximately 90% of the evacuees complete the evacuation, the mean evacuation rate reduces to a very low value. The evacuation rates for Cases A1 and A2 are 0.46per/s and 0.34 per/s in phase two, respectively. It means that the last few evacuees in both cases require more time to complete the evacuation. Therefore, attentions should be paid on the long tail effect during the evacuation process on the offshore platform, measures should also be taken to improve the evacuation rate of the last few evacuees.



(a) Evacuation time required for different ratios of cumulative evacuees



(b) Evacuation rates during the evacuation process

Fig.8 Distribution of evacuees versus evacuation time under normal visibility

3.2 Evacuation performance under constant restricted visibility

In this part, the evacuation with constant restricted visibility is studied. The situations can exist on offshore platforms such as night conditions with the failure of the power system, and foggy weather. The visibility during the evacuation process is almost at the same level, being called the constant restricted visibility. In order to study the evacuation of evacuees in these situations, three different visibility conditions including cases with fine visibility conditions (Cases B1 and B2), low visibility conditions (Cases B3 and B4) and very low visibility conditions (Cases B5 and B6) are simulated. These have been achieved by the FDS command "&INIT MASS_FRACTION = Calculated Value, SPEC_ID='SOOT'/". The extinction coefficients are reproduced by simulating a fictitious fuel made of 100% soot. Since the toxic effects of fire are not studied, "CO_YIELD = 0" is set in the commend line [31].

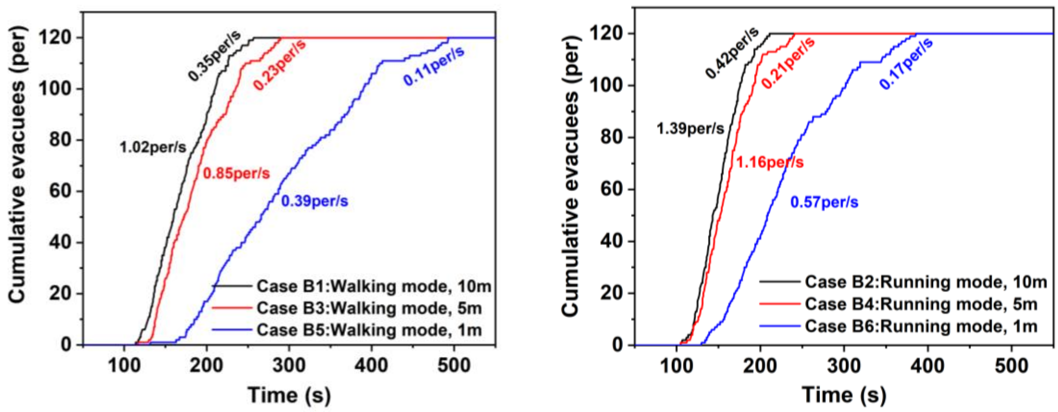
The reduction of visibility can result in reduced evacuation speed and increased evacuation time [18]. As SFPE handbook points that evacuees who know the internal geometry of the building in fire need a visibility of 4 m for safe escape while those who do not know the building geometry need a visibility of 13 m [3]. Consequently, the visibility of 10 m is regarded as a fine visibility condition in this research. In fact, slight difference can be found between Cases B1 and B2 as shown in Table 5 when compared with Cases A1 and A2. When the visibility continues to drop to 5 m, the mean walking speed and running speed are calculated as 1.04 m/s and 1.45 m/s respectively based on Eq.(2). The reduced evacuation speed causes an obvious increment of ETI and T_{que}. The total evacuation time increases over 20% in Cases B3 and B4 when compared with A1 and A2. Queuing time changes significantly, especially for the walking mode, the queuing time increases by 60.8% in Case B3. However, the increment of T_{que} in Case B4 is 34.4%. In this aspect, fast evacuation helps to reduce queuing in the living area.

When the visibility reduces to 1 m (almost complete darkness) in Cases B5 and B6, the evacuation process can be affected significantly as shown in Table 5. Since evacuees are in very low visibility areas, the evacuation speed can be extremely low in order to confirm the safety of frontal situation [10, 13]. Hence, evacuees move with the speed of 0.68 m/s for the running mode and 0.49 m/s for the walking mode based on Eq. (3). Compared with normal condition, evacuees in Cases B5 and B6 require nearly twice the time to complete the evacuation. Besides, the proportions of queuing time have also increased, which account for 43.7% and 34.2% of the total evacuation time in the living area. Taking Case B5 for an example, the arrival of evacuees from upper floors into Areas 1 and 2 (as shown in Fig.7) was delayed for the low evacuation speed. Queuing occurs around 142s as the upper-floor evacuees encounter the first-floor evacuees in Areas 1 and 2. The phenomenon lasts as the upper-floor evacuees continue gathering in Area 1 and 2, and ends around 277s. In emergency conditions, longer queuing time can lead to congestion and more casualties [26]. Proactive measures are suggested to reduce queuing time during evacuation.

Table 5 Simulation results of Case B

Case	$ETI_{working}$ (s)	ETI_{living} (s)	T_{que} (s)	QTI_{living}
B1	249.0±5.5	180.9±3.6	54.6±5.9	30.2%
B2	210.1±5.1	154.7±5.1	36.4±4.8	23.5%
B3	288.4±4.6	202.8±9.3	71.4±9.9	35.2%
B4	239.6±4.0	167.9±5.1	47.7±6.0	28.4%
B5	491.8±6.0	307.3±9.4	134.2±7.4	43.7%
B6	384.6±5.3	227.9±7.8	78.0±7.8	34.2%

To further study the distribution of evacuation time in each case from B1 to B6, the average evacuation rates are calculated as shown in Fig.9. It is observed that the six curves share similar trends with Cases A1 and A2 as shown in Fig.8 (b). The evacuation process in each case can also be divided into two phases roughly. In the first phase, the evacuation rate reduces as visibility drops. It is observed that the reduction of evacuation rate is sharper when visibility drops from 5 m to 1 m compared with visibility from 10 m to 5 m. Long tail effect still exists in the second phase, and the evacuation rate in the long tail also decreases as visibility drops. It is noted that when the visibility drops to 1 m, the evacuation rates in the second phase reduce to very low values (0.11per/s and 0.17per/s). In the second phase of Cases B5 and B6, the extra time taken to complete the evacuation by the last few evacuees is 79.8s and 66.6s, respectively.



(a) Walking mode (a) Running mode

Fig.9 Distribution of cumulative evacuees versus evacuation time in two modes under constant restricted visibility

3.3 Evacuation performance under intermittent restricted visibility

In this section, the single effect of low visibility caused by smoke on the evacuation is studied on the selected offshore platform. Fire occurs on the working deck due to the leakage of crude oil from the oil pipeline as shown in Fig.10.

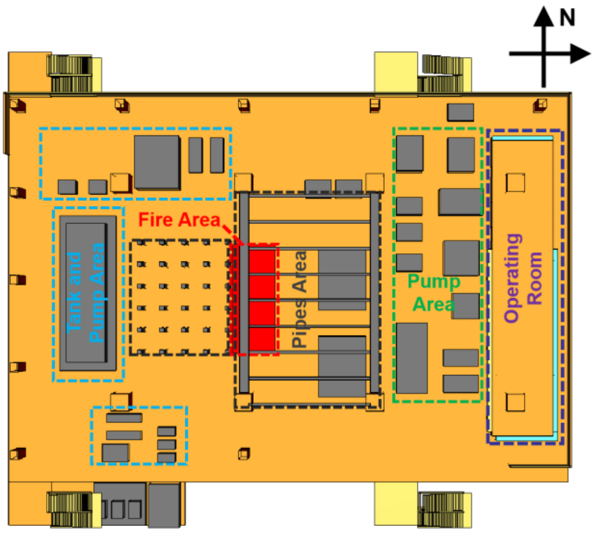


Fig.10 Layout of the working deck

Parameters of the pool fire are set as shown in Table 6. The pool fire is simulated using FDS 6.7.7 [32]. The validation work of the simulation model were carried in our previous research [33] .

Table 6 Parameters setting of the pool fire [3]

Parameter	Value

Fuel	Crude oil
Pool area (m^2)	63
Heat combustion of fuel (kJ/kg)	42600
CO yield (kg/kg)	0
Soot yield (kg/kg)	0.08

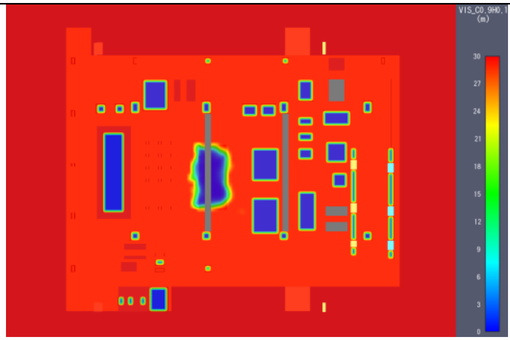
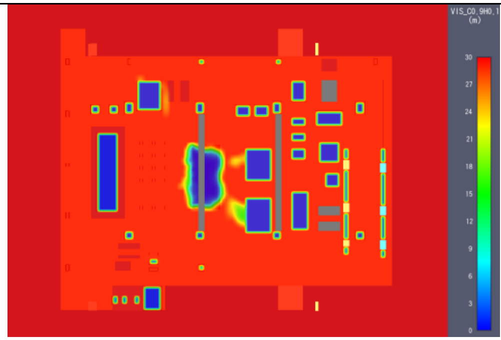
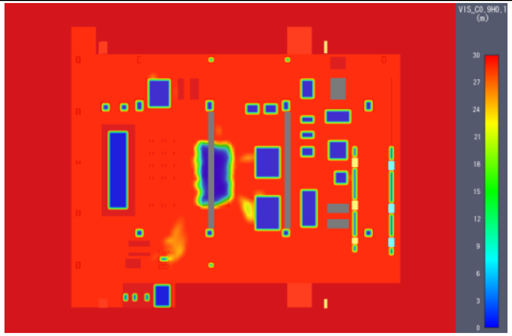
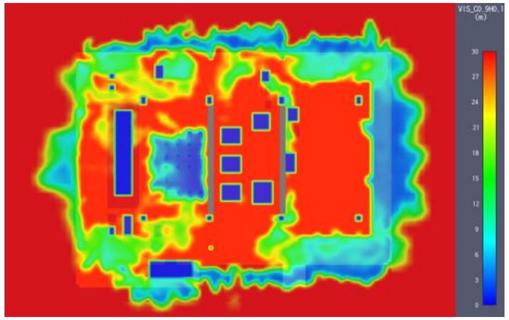
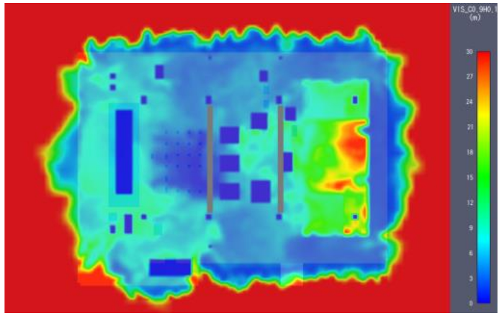
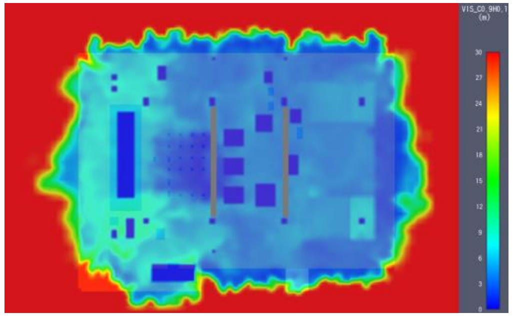
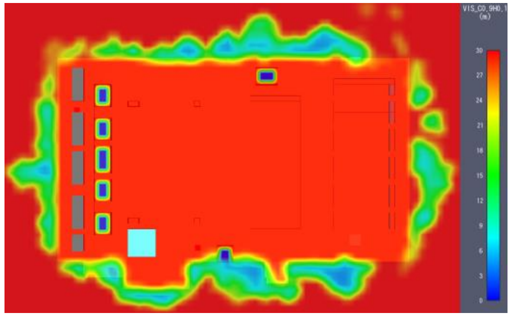
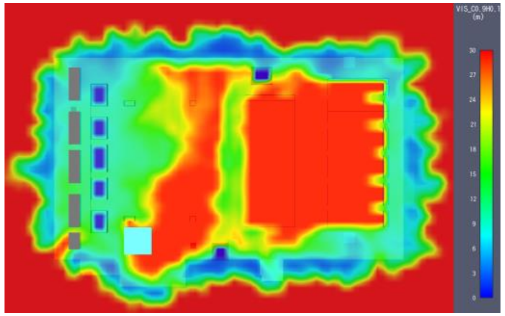
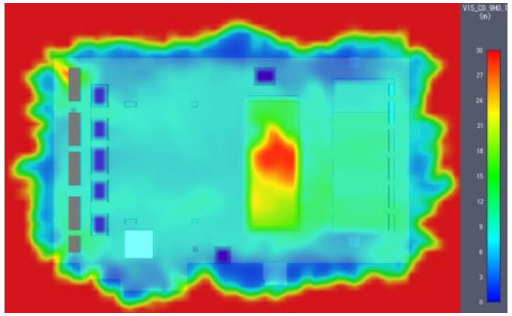
3.3.1 Distributions of visibility

Visibility is regarded as the most important factor influencing the evacuation [4, 12]. Different from Case B, the visibility in Case C is affected by smoke. As smoke spreads, the visibility at a certain location is variable. Therefore, the distribution of visibility caused by smoke on the offshore platform is analyzed in this section. The slices and devices for measuring the visibility were placed at a height of 1.6 m from each floor.

The spatial distributions of visibility on the working deck (elevation of 18.5 m), lower deck (elevation of 28.5 m) and upper deck (main deck, elevation of 38.5 m) at 90s, 150s and 300s after fire occurs are shown in Table 7. The pool fire occurs at 0s on the working deck and reaches the peak heat release rate around 101s. Since the research aims to study the effect of the visibility on the evacuation, the heat and toxic gases are not considered. As shown in Table 7, although the fire source locates on the working deck, the smoke does not have a great impact. The main reason is that the height between the working deck and the lower deck is 10 m, there is not enough smoke affecting the characteristic height of evacuees, except for the area close to the fire source. Therefore, the visibility of the most areas on the working deck maintains about 30 m. Comparatively, the visibility on the lower deck and the upper (main) deck are affected significantly. The smoke spread vertically upward mainly through the surrounding edges of the decks. As shown in Table 7, the visibility of the surrounding edges dropped to 10 m around 90s. Then as the smoke spreads horizontally, the most areas of the lower deck are affected, causing the visibility to reduce to 10 m around 150s. At 300s, the visibility of the entire lower deck reduces to 10 m, and in some areas, the visibility reaches less than 3 m. Although the upper (main) deck was less affected, the most areas were also surrounded by smoke at 300s after the occurrence of the fire.

Since staircases is regarded as key structures in vertical evacuation [8, 18], the variations of visibility in the staircases of the living area are analyzed. Visibility data is obtained from devices placed at 1.6 m high at different decks. As shown in Fig.11, the smoke firstly affects the staircases at the first floor around 100s, and the visibility at 1.6 m high dropped rapidly to less than 10 m. The visibility of the staircases at the second, third and fourth floor dropped to 10 m later around 130s. At 150s, the visibility in the living area reached a minimum value. The staircase at the first floor is the most affected with the visibility value of less than 5 m.

Table 7 Comparisons of visibility at 1.6 m high on different decks at the same time period

Different Decks	90s after fire occurs	150s after fire occurs	300s after fire occurs
Working Deck			
Lower Deck			
Upper (Main) Deck			

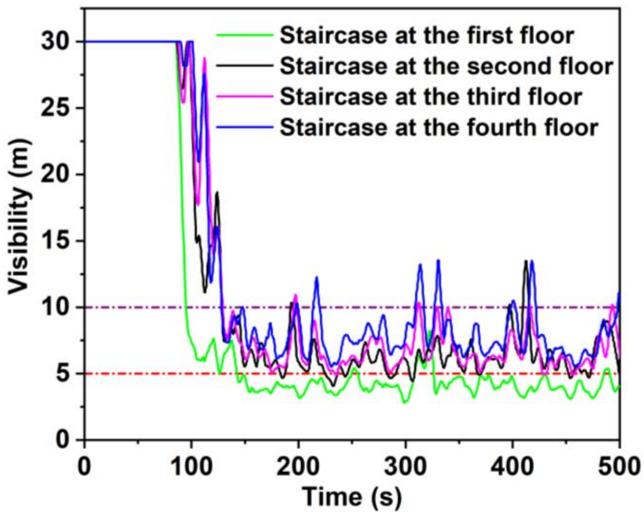


Fig.11 Visibility in staircases at different floors in the living area

3.3.2 Evacuation affected by visibility

The reduction of visibility in fire will not directly cause injury and deaths, however, it can result in the reduced evacuation speed and longer exposure time to heat and toxic gases [18]. Therefore, the effect of visibility on the evacuation was analyzed in this section. The simulation results of evacuation in fire accidents of Cases C1 and C2 are shown in Table 8.

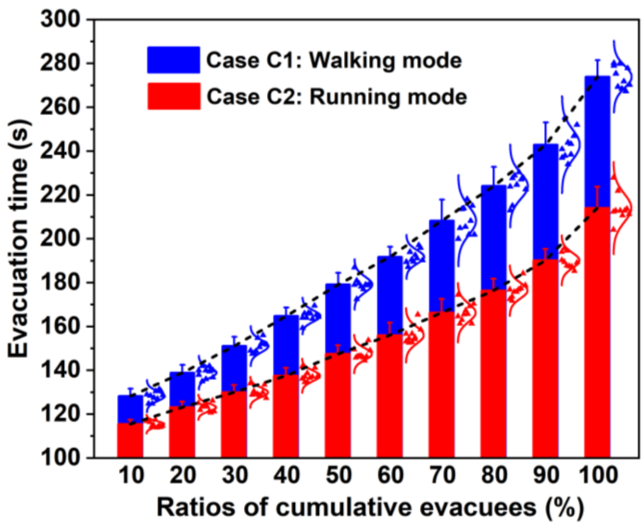
Compared to the normal condition of Cases A1 and A2, the evacuation time has increased obviously for Cases C1 and C2. Evacuees were less affected at the working deck, for the reason that the smoke does not have a great impact on this deck as the figures shown in Table 7. In fact, for Cases C1 and C2, the last person to leave the working deck is around 123.7s and 121s. It is close to the time for Cases A1 and A2 of 125s and 117s. However, as stated in Section 3.3.1, the lower deck and the upper (main) deck were affected by smoke significantly. The visibility on the lower and upper (main) decks starts to be affected and reduces to 10 m around 50s and 82s. Further, the low visibility areas (<10 m) cover almost the entire lower and upper (main) decks at 140s and 179s. Consequently, the evacuation time in the working area increased by approximately 40s and 30s for Cases C1 and C2 compared with Cases A1 and A2. Besides, the evacuation time in the living area has also increased. As the visibility in the living area reduced to 10 m around 138s, evacuees have to slow down their speed during the evacuation process. However, the slow evacuation speed of evacuees can lead to the congestion in Area 1 and Area 2 shown in Fig.7, and eventually increase the queuing time and evacuation time in the living area.

Table 8 Simulation results of Case C

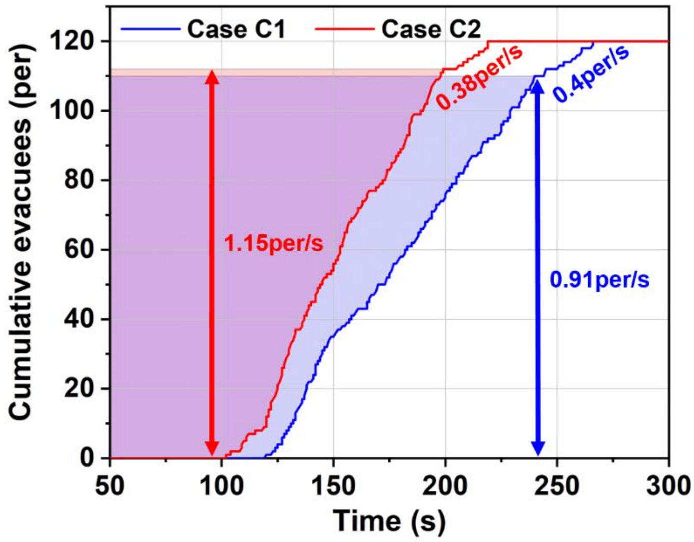
Case	$ETI_{working}$ (s)	ETI_{living} (s)	T_{que} (s)	QTI_{living}
C1	274.0±5.0	205.6±9.0	73.0±7.5	35.5%
C2	225.4±7.1	167.6±8.5	46.1±7.9	27.4%

The distributions of evacuation time in Cases C1 and C2 are discussed. The average evacuation times required for every 10% increase ratio of evacuees in two cases are shown in Fig.12 (a). The evacuation time gaps between Cases C1 and C2 for different ratios of evacuees are larger compared with Cases A1 and A2. As more evacuees complete the evacuation, the time gaps increase accordingly. It indicates that the evacuees with the walking mode are more vulnerable to low visibility in fire scene. As stated above, low visibility areas (<10m) cover almost the entire upper (main) decks at around 179s. However, according to Fig.12 (a), only 50% of evacuees complete the evacuation in Case C1 at this time. While for Case C2, 80% of evacuees have been evacuated. It means that half of the evacuees will be affected by the low visibility on the main deck in Case C1, while for Case C2, only a small number of evacuees can be affected. Hence, evacuees are advised to escape from the fire scene as fast as possible to reduce the risk of being exposed to fire hazards.

As shown in Fig.12 (b), the evacuation process can also be divided into two phases for Cases C1 and C2. The evacuation rates of the two phases are also investigated. In the first phase, due to the low visibility caused by smoke, the evacuation rates in Cases C1 and C2 drop from 1.13per/s and 1.52per/s to 0.91per/s and 1.15 per/s, respectively. However, the evacuation rate in the second phase is less affected when compared with Cases A1 and A2. The main reason is that evacuees on the working deck are rarely affected by the low-visibility smoke. As observed from Smokeview, the long tail effect is always caused by the evacuees from the working deck, because they have a longer evacuation path. However, for Cases C1 and C2, although the evacuation path has not changed, the evacuation speed is not affected significantly when evacuees on the working deck compared to the evacuees on other decks. As a result, the evacuation time required for the last 10% of evacuees is shortened, and the long tail effect can also be weakened.



(a) Evacuation time required for different ratios of cumulative evacuees



(b) Evacuation rates during the evacuation process

Fig.12 Distribution of evacuees versus evacuation time under intermittent restricted visibility

3.4 Comparisons of evacuation performance

In this research, different visibility conditions and evacuation modes are considered, comparisons of total evacuation time index (*ETI*), queuing time index (*QTI*), increment rate of the *ETI* (ω_{ETI}) and *QTI* (ω_{QTI}) caused by low visibility are discussed. As shown in Fig.13, visibility affects the evacuation speed, resulting in the increase of total evacuation time. As visibility becomes worse, the evacuation time required for evacuees will further increase. It is worth mentioning that when the visibility reduces to 5 m, the total evacuation time of evacuees does not change significantly, but is only about 1.2 times of that under normal condition. However, as the visibility drops to 1 m, under very low visibility conditions, the total evacuation time required in both evacuation modes can be doubled.

Queuing is observed in the living area. It mainly occurs at the first floor in the living area while evacuees from upper floors encounter those from the first floor at the staircase areas. As shown in Fig.13, the queuing time will also increase as the visibility becomes worse, because evacuees have to slow down their evacuation speed to confirm the safety of frontal situations. Slower evacuation speed can increase the queuing time. Under the very low visibility condition, the queuing time can be three times of that under normal visibility with the walking mode. However, compared with the walking mode, the queuing time can reduce when evacuees have the running mode. As visibility becomes worse, the advantage with the running mode for reducing queuing time becomes more apparent. Therefore, it is recommended that under safe evacuation, evacuees on the offshore platform should evacuate to the assembly station as quickly as possible, which will not only shorten the total evacuation time, but also ensure a shorter queuing time.

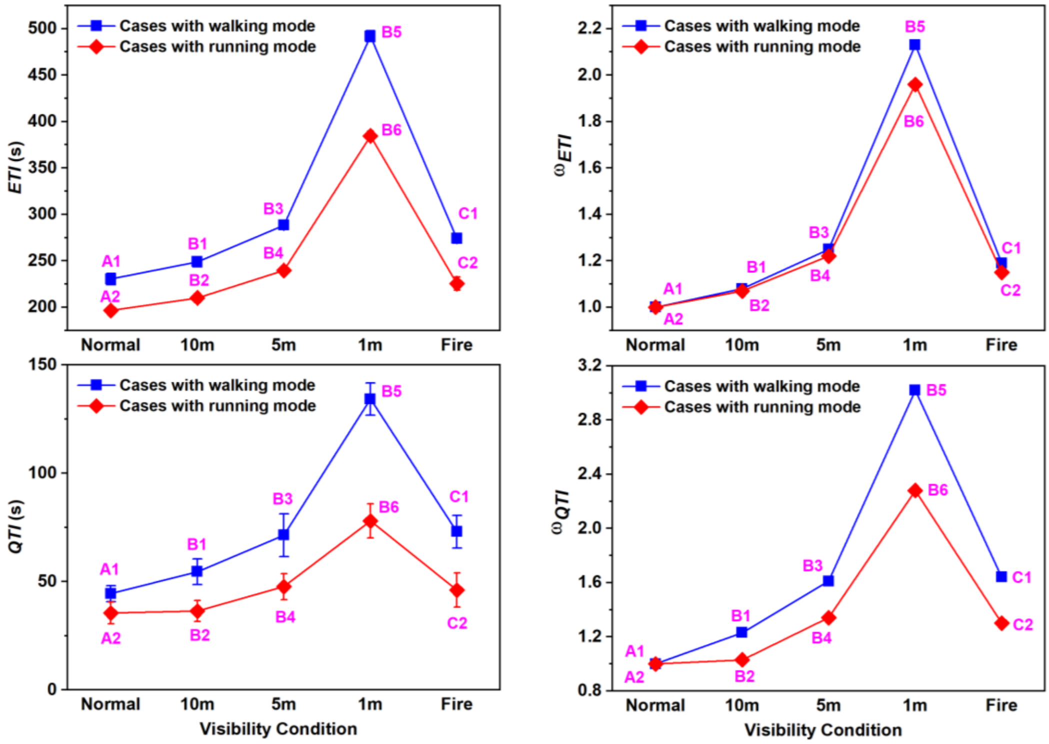


Fig.13 Comparisons of different evacuation indexes for different cases

The total evacuation time on the offshore platform is always affected by the evacuees in the working area ($ETI_{working}$) as discussed above. Long tail effect exists obviously in Cases A1 to B6 during the evacuation process. The reason for this phenomenon is that evacuees on the working deck and lower deck have a longer evacuation distance than evacuees on other decks do. According to the simulation results, the last few evacuees were always from the working deck and lower deck. From Fig. 14, for Cases A1 to B6, the increase of evacuation time for the last few evacuees in the second phase is about 3 times the average of 10% increase ratio of evacuees in the first phase. However, different from Cases A1 to B6, the working deck in Cases C1 and C2 is less affected by visibility than other decks, which can ensure that the evacuees on the working deck can leave faster. Consequently, compared with other cases, the evacuation speed on the working deck is less affected in Cases C1 and C2, and this plays an important role in alleviating the long tail effect.

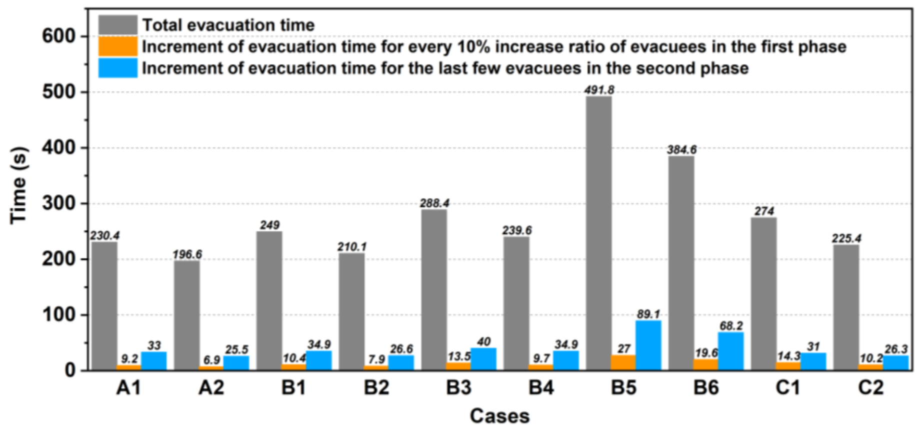


Fig.14 Time required for different portions of evacuees

3.5 Measures to improve the evacuation efficiency

Since the long tail effect can affect the evacuation time obviously in Cases B1 to B6, and result in the increased risk of exposing to hazards. Therefore, measures should be taken to improve the evacuation efficiency of evacuees on the working deck and lower deck. In this study, combined with previous offshore platform accidents, two aspects to reduce the long tail effect were considered as follows.

(1) Shorter Evacuation Distance

In this study, the main reason for the long tail is that the evacuees on the working deck have a longer evacuation distance. Besides, due to some unexcepted reasons, evacuees change their routes to the assembly station, which results in the increase of evacuation distance. This was the situation in the Deepwater Horizon accident, while evacuees had to re-plan their evacuation routes for the reason that some pre-planned routes were blocked and impaired. Taking this situation into account, in order to shorten the distance between evacuees on the working deck and the lifeboats, the location arrangement of the lifeboats are modified. One of the two lifeboats on the east side of the main deck is placed on the west side, and the effect of this modification on the long tail effect and the total evacuation time are investigated.

The purpose of this measure is to provide a convenient evacuation way for evacuees on the working deck and lower deck because the evacuees on both decks are the key factors resulting in the long tail effect. The comparison results before and after taking the measure are shown in Fig.15. It is validated that a proper arrangement of the lifeboats on the offshore platforms can help to reduce the long tail effect. As a result, the total evacuation time can be reduced by 5% to 15% in these cases. This can provide guidance for the layout arrangement of evacuation facilities for offshore platforms.

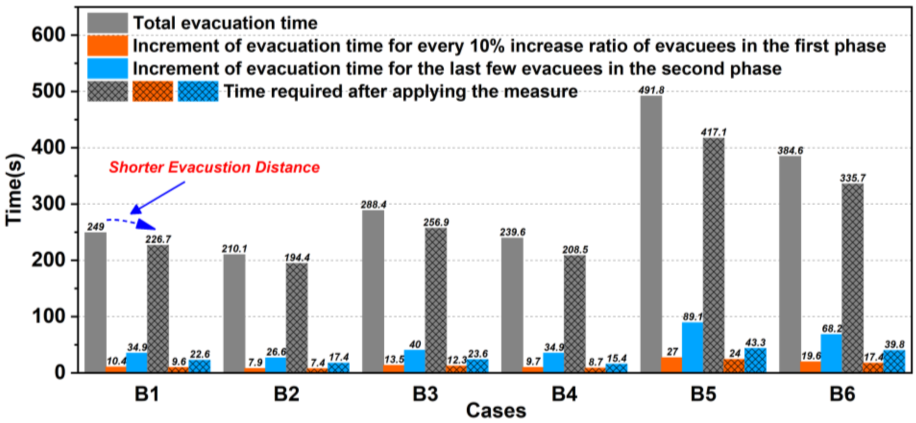


Fig.15 Comparisons after applying the measure “Shorter Evacuation Distance"

(2) Faster Response Speed

According to the survey records of survivors in the Deepwater Horizon accident, the evacuation was delayed by some workers as they did not see or hear any alarms after the explosion [2]. Longer response time of workers far away from the assembly station could also result in the long tail effect. In this aspect, workers should respond quickly when alarms are raised to complete the evacuation urgently in the event of an accident.

In order to verify the effect of this measure on the long tail effect, the mean response time of evacuees on the working deck and lower deck are reduced to 30s and 60s respectively, and the mean response time of other decks remains unchanged. The results are shown in Fig.16. Since the measure “Shorter Response Time” is taken by evacuees on the working deck and lower deck, the long tail effect is reduced significantly. More importantly, the total evacuation time can be reduced by 10% to 20% in Cases B1 to B6. In practice, the measure can be achieved by evacuation drills to improve workers’ spatial awareness, alarm recognition and emergency response procedures [34]. Besides, in the premise that the alarm is given unmistakable, workers are supposed to use the alarm identification rule correctly and respond immediately. Just as required by the Petroleum Safety Authority Norway Activity Regulation [35], that “*the right alert is given immediately*” and “*the personnel on the facility can be quickly and efficiently evacuated at all times*”.

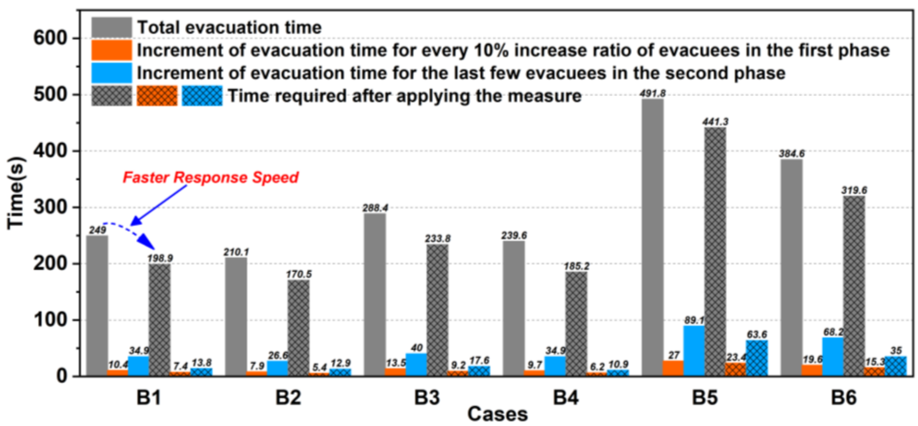


Fig.16 Comparisons after applying the measure “Faster Response Speed"

4. **Conclusions**

In this study, a series of evacuation simulation cases are designed to investigate the evacuation characteristics under different visibility conditions and evacuation modes on a selected offshore platform. Conclusions obtained from the simulation results are summarized as follows:

(1) The total evacuation time will further increase as visibility becomes worse. When the visibility drops to 5 m, the evacuation time increases slightly for about 1.2 times of that under normal visibility condition. However, when the visibility drops from 5 m to 1 m, the evacuation rates decrease significantly, and the total evacuation time can be doubled.

(2) Queuing mainly occurs in the living area, and queuing time increases when the visibility becomes worse or personnel evacuate with the walking mode during the evacuation process. Besides, as the visibility becomes worse, the advantage with the running mode for reducing queuing time is more apparent. It is recommended that evacuees move as quickly as possible to reduce both the queuing time and the total evacuation time.

(3) Since evacuees on the working deck and lower deck have a longer evacuation distance than evacuees on other decks do during the evacuation process, long tail effect thus exists obviously in Case A and Case B. It means that the evacuation time for the last 10% evacuees can be pretty long. Combined with the evacuation process in the Deepwater Horizon accident, targeted evacuation measures are then proposed. As a result, the long tail effect is alleviated, and more importantly, the total evacuation time in Cases B1 to B6 can be reduced significantly.

Focusing on the evacuation process affected by restricted visibility, the study provides an efficient strategy for the evacuation of personnel in restricted visibility environments on offshore platforms. However, in the research, only the effect of visibility on the evacuation of personnel is considered, and the impact of other fire factors, such as heat radiation and toxic gases, is not involved. In future research, more influencing factors should be investigated to study their combined effect on the evacuation of personnel on offshore platforms.

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