# STUDY ON EVALUATION OF ESCAPE ROUTE IN PASSENGER SHIPS BY EVACUATION SIMULATION AND FULL-SCALE TRIALS

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**SUMMARY**

*Evaluation of effectiveness of escape routes in passenger ships in its design stage has recently become an important issue for the maritime safety. Several techniques of computer simulation on egress behavior of people has been and is being developed in both land based application (for building) and marine application (for ships). In order to develop accurate simulation techniques, actual information and data on egress behavior of people are anticipated. A full-scale trial of evacuation using a passenger ferry and students of a maritime academy was carried out in Japan. And some additional full-scale measurements of flow coefficients of walking people in inclined or rolling walkways were made. This paper presents the results of such full-scale trials and results of simulations for such full-scale trials.*

**INTRODUCTION**

It is important to design, for ships and offshore structures, effective escape routes, which should provide smooth escape of passengers and crew without any congestion and confusion when they should abandon the ship or offshore structure in an emergency event. International maritime regulations (International Convention for the Safety of Life at Sea: SOLAS) require two escape routes from any spaces and prohibit dead-end corridors in ships. The regulations also require determining width of escape routes in ships by a simple calculation method [1].

After the tragedy of the passenger ferry "ESTONIA", a requirement on evaluation of effectiveness of escape routes in passenger ferries in the early design stage has been added to SOLAS. In responding this new requirement, Fire Protection Sub-Committee of IMO (International Maritime Organization) developed, as an interim measure, a guidelines for simplified evacuation analysis method for such ships [2].

Very large passenger cruise ships, which gross tonnage is more than 100,000 tones, have been built in this two-three years period and this trend will continue in future. The number of passengers boarding on such ships will be more than 3,000. IMO is now considering the safety of such large passenger ships. Safety evacuation is, of cause, one of the major topics within this consideration. [3]

In these circumstances, it is anticipated, in the maritime field, to develop more precise and accurate evaluation technique for effectiveness of escape routes based upon computerized numerical simulation method for ships and offshore structures. In order to develop such techniques, full-scale data on movement of people in evacuation process is also desired.

Therefore, a full-scale evacuation trial was conducted using a passenger ferry and about 400 students of a maritime academy. Based on the trial, a numerical simulation method for evacuation is being developed. This paper reports the results of the trial and the development.

## NUMERICAL SIMULATION METHOD ON EVACUATION

It would be possible to evaluate the effectiveness of escape routes by trials using people when a passenger ferry has been built. However, the international regulation requires evaluating the effectiveness in the early design stage of passenger ferries and, if necessary, the design should be changed in proactive manor to avoid any congestion, which might happen in the escape routes. In order to conduct such evaluations in design stage of passenger ships, numerical simulation techniques on egress behavior of people through escape routes should be used.

New techniques on computer-based evacuation models simulating the movement of individual persons (individuals movement model) have been developed recently, for example [4], [5] and [6], in which the personality and mentality of individuals may be presented.

There have been developed numerical simulation techniques in which people are treated as a group or crowd (crowd movement model) and have been used in actual evaluation of escape routes in buildings [7]. In this model, it is assumed that people in a space or under a condition are deemed to behave in a same manor, and crowd is treated as a flow with a flow coefficient (passing person per second per unit width (m): [Person/s/m]) in corridors and at openings. This model can be relatively easily dealt with and seems preferable for the purpose of evaluation of escape routs in early design stages. In addition, passengers are to be guided by crew in emergency cases in ships, and may move in a same manor under such guide. This also suggests the applicability of the crowd movement model for passenger ships. Such crowd movement model is used in this study. The computer program written in Visual BASIC used in this study has been developed based on the literature [7], taking into account the characteristics of ships.

## FULL-SCALE EVACUATIN TRIAL

### The Ship and Environment

A full-scale evacuation trial was conducted on a passenger ferry moored at Port of Onahama, Ibaragi, Japan on October 20, 1997. The ferry was a domestic class passenger ferry and did not fully comply with SOLAS but complied with National regulations for ships of Japan. The particular of the ferry is given in Table-1. Ambient temperature was 16 to 21.5 $^{o}$C and the wind was 3 to 5 m/s in SW direction during the trial.

**Table-1 Particular of the ferry**

| | |
|---|---|
| Gross Tones: 11,782 | built: 1993 |
| Over-all Length: 186.00 m | Length between perpendicular: 170.00 m |
| Width molded: 25.50 m | |
| Depth molded: 18.01 m | Draught full load: 6.60 m |
| Passenger: 514 | Officer and Crew: 28 |
| Liferaft: capacity 50 x 13 | Shooter (Evacuation slide): 3 |
| Rigid rescue boat: 1 | |

The ferry has two passenger decks. Cabins are distributed on both sides of the hull, and large passenger rooms, restaurant, cafeteria and galley are situated along the center of the ship. Crew area is situated on the top-deck aft of the navigation bridge.

### Distribution of Passenger and Crew

Total 356 students and teachers of Oarai Fishery High-School and 27 officers and crew of the ferry were joined the trial. All the testees wore, over their life jacket, a numbered cloth to which bar-cord marks were also attached. Each testee was assigned a cabin. Distribution of the testees and their grouping is shown in Figure-2 and table-2. One group of passengers was guided by a passenger attendance (crew). The cabins on the portside and in the center which occupants were ordered to assemble to the portside assembly station (top deck) were fully occupied by 245 testees. Other 111 testees were allocated in the starboard-side cabins. Before the trial, no instruction on escape routes and method of egress and abandonment was given to the testees prior to the trial. Such instruction was given during the trial by the passenger attendances. At the start of the trial, they scattered randomly in the ferry.

**Table-2 Scatter and Grouping of Passengers**

| Group | Deck | Space | Number | Note |
|---|---|---|---|---|
| 3 | A | Starboard large passenger room | 52 | Starboard assembling |
| 4a | A | Portside large passenger room | 24 | Portside assembling |
| 4b | A | Portside large passenger room | 30 | Portside assembling |
| 5 | A | Special and 1st class cabins | 39 | Portside assembling |
| 7 | B | Starboard large passenger room | 59 | Starboard assembling |
| 8a | B | Portside large passenger room | 42 | Portside assembling |
| 8b | B | Portside large passenger room | 42 | Portside assembling |
| 9a | B | 1st class cabins | 42 | Portside assembling |
| 9b | B | 1st class and 2nd class cabins | 26 | Portside assembling |

### Scenario

The scenario of the trial is shown in Figure-1. The main events were as follows:

(1) Fire calls (for fire at the galley); crew were assigned for fire fighting.
(2) Announcement to passengers; to go back their cabin and stay.
(3) Crew assigned as passenger attendance instructed the passengers to wear life jacket.
(4) Passengers stayed in their cabins.
(5) Evacuation order by the Captain.
(6) Crew assigned as passenger attendance guided the passengers to the assembly station.
(7) Crew assigned to survival appliances started lowing rescue boat, liferafts and shooter evacuation slide.
(8) Crew assigned to navigate the liferafts went down through the shooter and prepare the platform and the liferafts.
(9) The passengers went down to the platform through the shooter and embark into the liferaft.

### Observation Methods

Total 26 of video cameras were installed along the escape routes and assembly station and in a boat about 150 m off the ferry. The bar codes were read at the entrance of the assembly station.

The testees were identified by the number they wore and their movements were traced by these video cameras and bar-code readings.

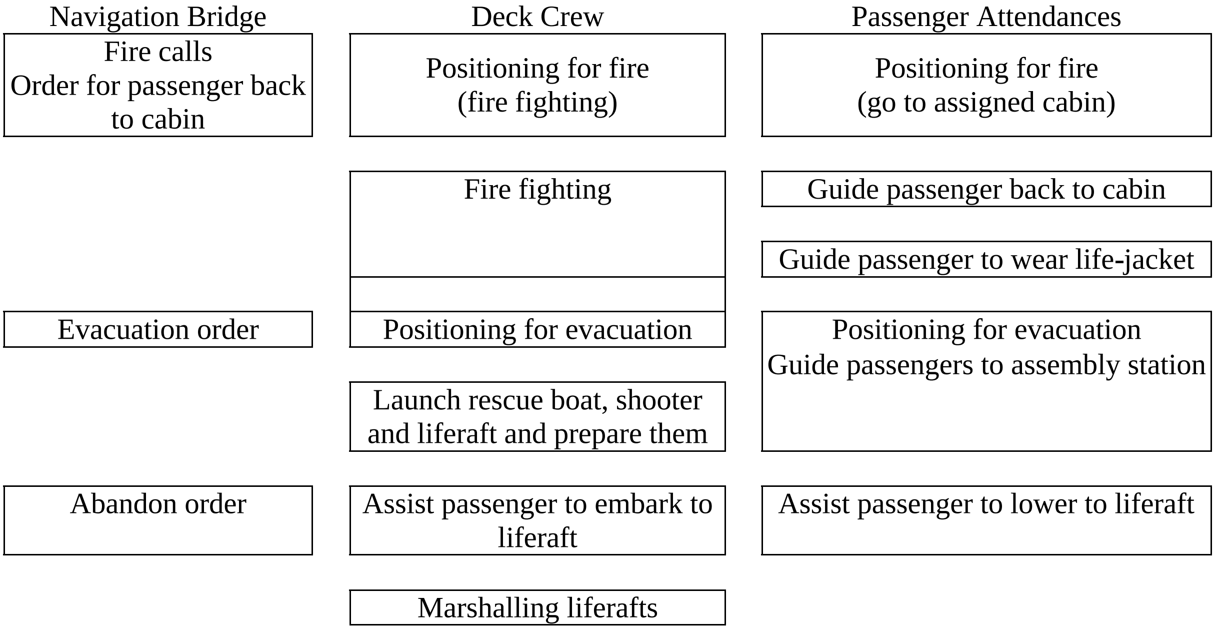



**Figure-1 Scenario of the trial**

## RESULTS OF THE TRIAL

The trial was included the egress of passengers through escape routes and their abandonment of the ship using shooter evacuation slide and lifeboat. However, the main topic of this paper is of the egress part. Therefore, this paper describes mainly the results of egress process through escape routes.

Table-3 shows the events and their time of occurrence. The long duration of abandonment was the results of the operation of abandonment, where people lowered through the shooter evacuation slide with a long interval in order to avoid any injury by clash in the shooter. The discussion about the abandonment would be presented in another paper.

All the passengers went back to their cabins within 13 minutes from the first announcement. They wore lifejacket in another 13 minutes. This duration included the duration of staying cabin and waiting for the next order. After the evacuation order at 10:46:58, the passenger attendances guided, according to the emergency instruction, the passengers of their responsibility to the assembly station. The start of the guide was cascaded according to the instruction, in order to avoid congestion in the escape routs. In other words, one group started egress about 1 minute after the adjacent group started.

Total 152 passengers used the spiral stairway. Then, congestion was observed at the spiral stairway. Total 245 passengers should go through the exit to assembly station in top deck. Another congestion was observed at the exit. The congestion at the exit also resulted in slow-down of movement and congestion in the spiral stairway. Most of the 245 passengers came proximity of the assembly station within about 7 minutes. However, due to the congestion at the exit, it took 11 minutes to complete the assembly. One person in group 3 and 3 persons in group 7 came to the portside assembly station. Therefore, total 249 passengers assembled to the portside assembly station. Figure-2 shows the movement of passengers during the trial. Figure-3 shows the number of passengers of groups arrived at the portside assembly station.

**Table-3 Observed sequence of the trial (time in AM)**

| Movement | Start at hh:mm:ss | End at hh:mm:ss | Duration mm:ss | Notes |
|---|---|---|---|---|
| Fire call | 10:15:00 | | | |
| Passengers return to cabins | | 10:27:50 | 12:50 | Duration for return to cabin |
| Order to wear lifejacket | 10:33:22 | 10:46:10 | 12:48 | Duration for wear lifejacket |
| Evacuation order | 10:46:58 | | | |
| Announcement to passenger | 10:47:43 | | | |
| Guide starboard-side passengers to assembly station | 10:47:45 | 10:52:05 | 4:20 | Duration of egress to assembly station |
| Guide portside passengers to assembly station | 10:47:50 | 10:58:00 | 10:10 | Duration of egress to close to the assembly station |
| Order for launching | 10:57:25 | | | |
| Launch rescue boat | 10:57:40 | 11:04:25 | 6:45 | |
| Launch shooter slide | 11:04:56 | 11:07:00 | 2:04 | |
| Launch liferafts | 11:06:37 | 11:10:51 | 4:14 | |
| Prepare shooter, platform and liferafts for passenger lowering | 11:11:31 | 11:18:50 | 7:19 | |
| Passenger abandonment and embarkation to 5 liferafts | 11:20:20 | 12:43:52 | 1:23:32 | Duration of 249 passengers embarking into 5 liferafts |

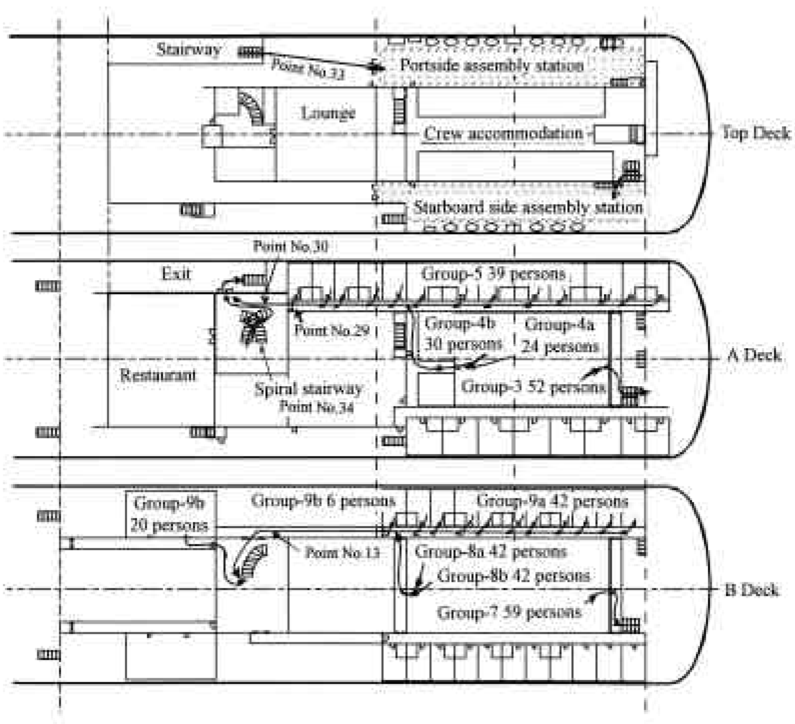



**Figure-2 Egress Movement of Passengers**

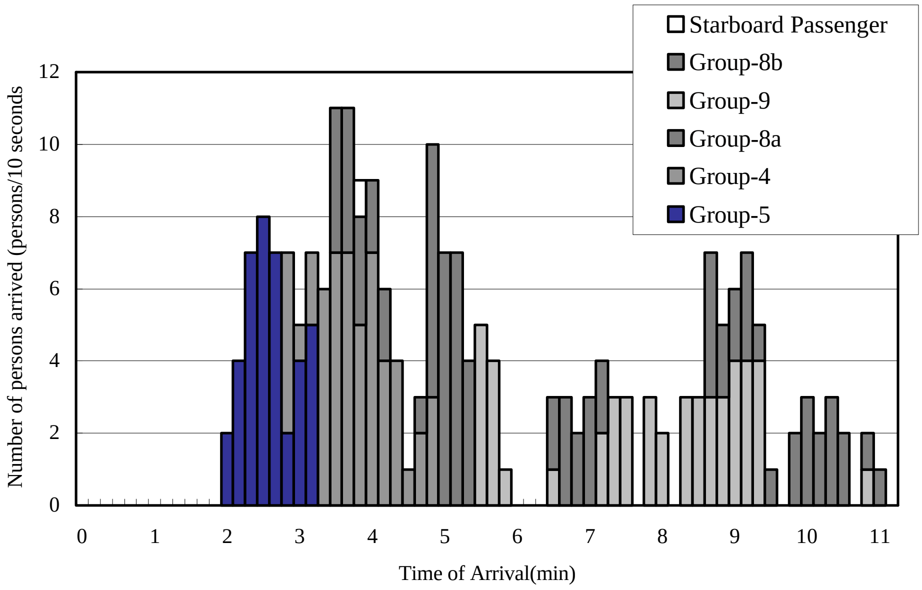



**Figure-3 Number of Passengers of groups Arrived at the Portside Assembly Station**

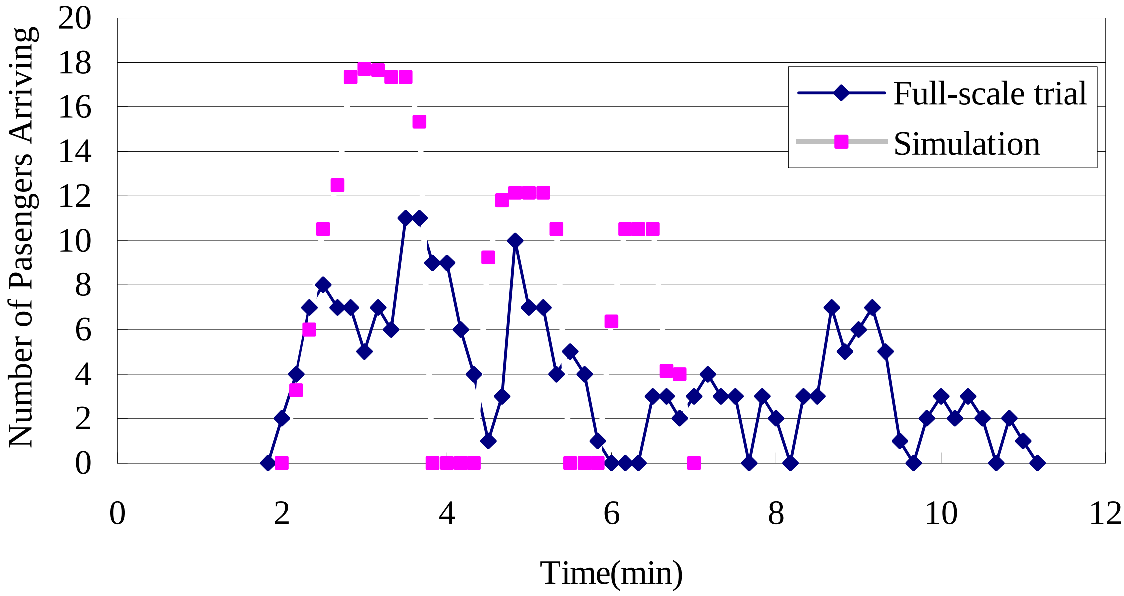
## SIMULATIONS

The simulation technique used in this study was a crowd movement model as shortly described above. There are some assumptions in this program as follows:

(1) Rooms where people stay, such as cabins and restaurants, have exits where people only flow out and never come into;
(2) In the rooms where more than one exits exist, people may seek the least congested exit;
(2) A corridor is divided into and treated as separate spaces where the width is changed;
(3) A space that has more than one entrance or exit is dealt with as "Hall" where people may seek the least congested exit.
(4) Passengers and crew walk in a constant speed of 0.8 m/s in rooms and corridors and 0.3 m/s (speed in horizontal direction) in stairways.
(5) Flow coefficient at openings was fixed at 1.5 person/s/m.
(6) Maximum capacity for all spaces was set at 5 person/m$^2$.

The computer simulation started when order of evacuation was made. At that time, all the passengers had come back to their cabin and worn lifejackets. The passengers were guided by the designated passenger attendances. Starting time of evacuation was different among the passenger groups in the full-scale trial. The simulation also simulated this cascaded start of evacuation.

Figure-4 shows a comparison between the result of the full-scale trial and the simulation on number of passenger arriving at the portside assembly station. There can be observed a relatively good agreement between them until 6 minutes from the start. Then after, there is a significant difference. The reason of the difference would be that in the full-scale trial the passenger congested at the entrance of the assembly station even the occupant ratio in the assembly station was less than 5 person/m$^2$, and due to such event, another congestion happened at the outside stairway leading to the assembly station. The simulation could not well realize such a happening.




**Fiogure-4 Comparison between the full-scale trial and the simulation by number of person arrived at the portside assembly station**

Figure-5 shows other simulation results on number of passengers stayed (stop walking) at some positions in the escape routes. The positions of the escape routes are shown in Figure-2. The largest congestion happened at the outside stairway leading to the portside assembly station. The second large congestion happened at the entrance of spiral stairway on A deck where passengers coming from B deck through the spiral stairway and passengers coming from the corridor of A deck met. These phenomena were observed also at the full-scale trial.

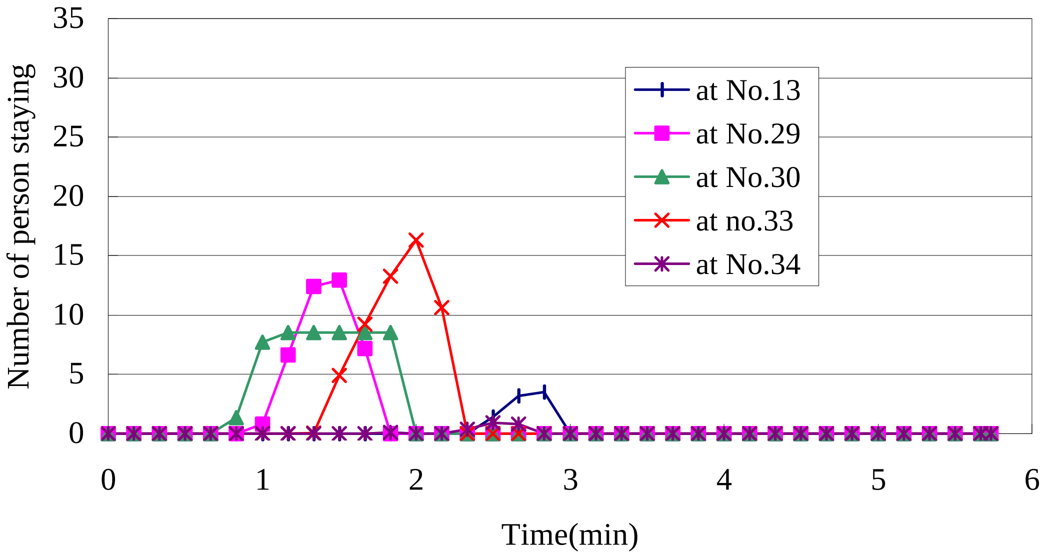



**Figure-5 number of passengers stayed (stop walking) at some parts of the corridors (Simulation for the case of cascaded evacuation starting)**

Figure-6 shows a simulation results on number of passenger stayed at the same positions in the escape routes in case that evacuation of all of the groups started at once. The degree of congestion is bigger than that shown in Figure-5. This shows that the guide of passengers by passenger attendances is very important for smooth evacuation.

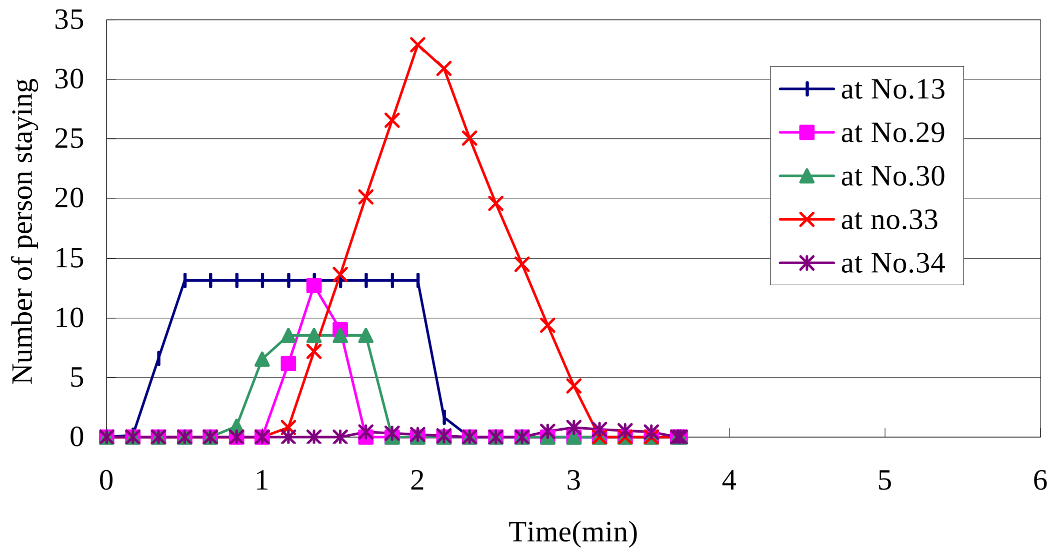



**Figure-6 number of passengers stayed (stop walking) at some parts of the corridors (Simulation for the simultaneous evacuation starting)**

**MESUREMENT OF FLOW COEFFICINTS IN INCLINED WALKWAY**

Conditions of escape routes peculiar to ships is inclination of walkway when the ship floods and coaming at entrances to spaces. The coaming is usually arranged in order to stop movement of water. There was no data of flow coefficient of people in such conditions. Therefore, walking speed and flow coefficient (number of persons passing a position of walkway per second per unit width) were measured using 21 people and full-scale models of walkway, which incline in various conditions. In addition, an additional trail in which a person walked in the opposite direction against the passenger movement was carried out to simulate the case that crew goes, for a duty at emergency, in the opposite direction against passengers' evacuation movement.

**Test Method**

Models of walkways used for static inclination tests had the length of 6 m and width of 1.2 m, 0.9 m and 0.6 m. Another model of walkway of length of 3 m was used for dynamic inclination test (in pitching and rolling motion). Panels on one side and the ceiling of the walkway were removed and poles were attached instead in the wall and ceiling position in 1 m interval for measurement of walking speed of people by video cameras. In some cases, 0.23 m height coaming and door frame (opening width was 0.6 m or 0.9 m) were attached in the middle of the model of walkway. Table-4 and figure-7 summarize the test conditions. 21 people were used for the static inclination tests and 6 people were used for the dynamic inclination tests. Height and weight of these people are shown in Table-5.

**Table-4 Test conditions**

| | | |
|---|---|---|
| Static inclination tests | Length of walkway | 12 m |
| | Width of walkway | 1.2 m, 0.9 m and 0.6 m |
| | Fore and aft inclination | +20, +10, 0, -10, -20 degree (Minus means downward walkway) |
| | Side inclination | 20, 10, 0 degree (right-side down) |
| Dynamic inclination test | Length of walkway | 3 m |
| | Width of walkway | 0.9 m |
| | Roll and pitch cycle | 5 seconds and 10 seconds |
| | Inclination | 10 degree |
| Coaming | Height | 0.23 m |
| Doorframe | Opening width | 0.6 m, 0.9 m |

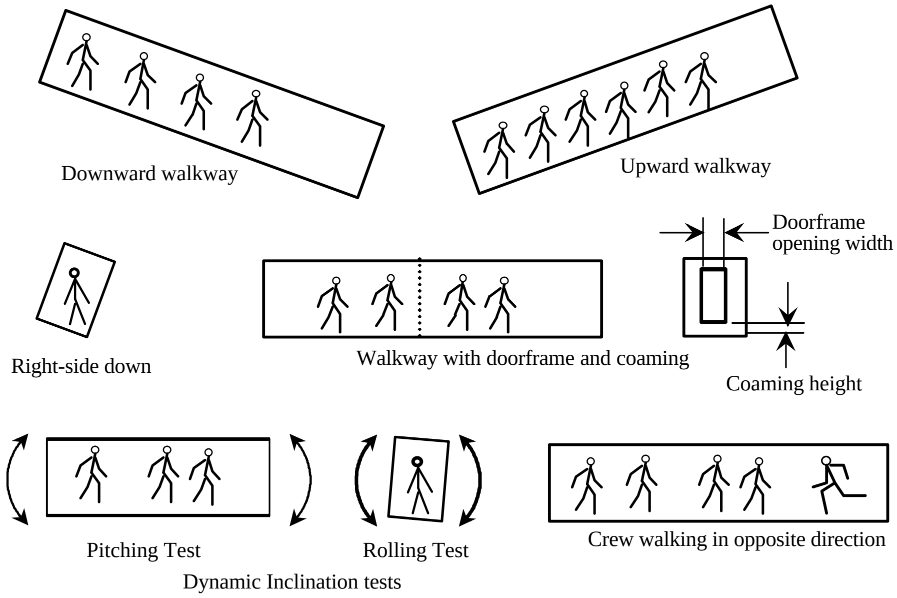



**Figure-7 Test conditions on inclined walkways**

**Table-5 Particular of people**

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Height (m) | 1.71 | 1.72 | 1.65 | 1.71 | 1.78 | 1.71 | 1.80 | 1.75 | 1.75 | 1.73 | 1.75 |
| Weight (kg) | 69 | 77 | 58 | 64 | 79 | 59 | 73 | 86 | 90 | 80 | 75 |
| Sex | M | M | M | M | M | M | M | M | M | M | M |
| No. | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | |
| Height (m) | 1.70 | 1.79 | 1.67 | 1.68 | 1.62 | 1.81 | 1.64 | 1.56 | 1.58 | 1.73 | |
| Weight (kg) | 67 | 71 | 70 | 61 | 61 | 74 | 73 | 51 | 56 | 67 | |
| Sex | M | M | M | M | M | M | M | F | F | M | |

**Results of Static Inclination Test**

Walking speed (m/s), flow coefficient (number of persons passing a position of walkway per second per unit width: person/s/m) and density of people (person/m$^2$) were observed in various conditions of inclination of walkways. The measured results are summarized in Table-6. In case of the downward walkway, the walking speed increased, but density decreased because people wished to keep longer distance from the people walking in front. In case of right side down walkway, people could walk only on the right side and the density deceased.

**Table-6 Results of Static Inclination Test**

| Condition | Width of walkway (m) | Walking speed (m/s) | Flow coefficient (person/s/m) | Density (person/m$^2$) |
|---|---|---|---|---|
| Even level | 1.2 | 1.23 | 2.16 | 1.0 |
| | 0.9 | 1.28 | 2.24 | 1.0 |
| | 0.6 | 1.25 | 1.96 | 0.9 |
| 20 degrees upward | 1.2 | 0.82 | 1.39 | 1.0 |
| 10 degrees upward | 1.2 | 1.09 | 1.80 | 0.9 |
| 10 degrees downward | 1.2 | 1.37 | 1.63 | 0.7 |
| 20 degrees downward | 1.2 | 1.38 | 1.28 | 0.5 |
| 10 degrees right-side down | 1.2 | 1.31 | 1.75 | 0.8 |
| 20 degrees right-side down | 1.2 | 1.23 | 1.19 | 0.6 |

**Results of Dynamic Inclination Test (Pitching and Rolling)**

The length of walkway for Dynamic inclination test was limited to 3 m due to the size of rolling table. One person walked in the walkway under rolling and pitching conditions and walking speed was measured. Table-7 summarizes the results. The walking speed under rolling or pitching condition was approximately 70 % of that in even level condition.

**Table-7 Results of Dynamic inclination Test (Pitching and Rolling)**

| Condition | Cycle | Walking speed (m/s) |
|---|---|---|
| Even level (no roll or pitch) | ----- | 0.90 |
| Pitching in 10 degrees | 10 seconds | 0.73 |
| | 5 seconds | 0.71 |
| Rolling in 10 degrees | 10 seconds | 0.77 |
| | 5 seconds | 0.72 |

**Flow Coefficient Passing Doorframe and Coaming**

A doorframe with coaming (height: 0.23 m) or without coaming was put in the midway of the model of walkway, and people walked through the walkway as shown in figure-7. In this case, walkway itself was put even level (no inclination). Table-8 summarizes the results. The flow coefficient was decreased by about 20 %.

The walkway with doorframe (but without coaming) was inclined and flow coefficient was measured. Table-9 summarizes the results. It seemed difficult to walk through doorframe opening when walkway inclined in right-side down.

**<u>Table-8 Flow coefficient at doorframe with coaming</u>**

| Condition | Width of walkway (m) | Width of doorframe opening (m) | Flow coefficient (person/s/m) |
|---|---|---|---|
| Doorframe with coaming | 1.2 | 0.9 | 2.43 |
| | 1.2 | 0.6 | 2.37 |
| | 0.9 | 0.6 | 2.57 |
| Doorframe without coaming | 1.2 | 0.9 | 2.04 |
| | 1.2 | 0.6 | 1.97 |
| | 0.9 | 0.6 | 1.93 |

**<u>Table-9 Flow coefficient at doorframe (with coaming) in inclined walkway</u>**

| Condition | Width of doorframe opening (m) | Flow coefficient (person/s/m) |
|---|---|---|
| 20 degrees upward | 0.9 | 2.02 |
| 10 degrees upward | | 2.50 |
| Even level | | 2.43 |
| 10 degrees downward | | 2.71 |
| 20 degrees downward | | 2.39 |
| 20 degrees upward | 0.6 | 2.11 |
| 10 degrees upward | | 2.55 |
| Even level | | 2.36 |
| 10 degrees downward | | 2.53 |
| 20 degrees downward | | 2.48 |
| 10 degrees right-side down | 0.9 | 2.13 |
| 20 degrees right-side down | | 1.62 |
| 10 degrees right-side down | 0.6 | 2.10 |
| 20 degrees right-side down | | 1.63 |

**Flow When a Crew walks in Opposite Direction**

Walking speed and flow coefficient were measured in case that a person walked in opposite direction against passengers as shown in Figure-7. Table-10 summarizes the results. The walking speed of both crew and passenger deceased and was about 50 % of normal condition (without oncoming walking crew). The walkway was kept in even level condition (no inclination nor doorframe).

**<u>Table-10 Walking speed and flow coefficient When oncoming crew exist</u>**

| Width of Walkway (m) | Passengers | | Crew |
|---|---|---|---|
| | Walking speed (m) | Flow coefficient (person/s/m) | Walking speed (m) |
| 0.6 | 0.78 | 1.86 | 1.00 |
| 0.9 | 0.60 | 2.13 | 0.98 |
| 1.2 | 0.93 | 2.22 | 0.97 |

## CONLUSIONS

- The results of the full-scale trial of evacuation carried out on passenger ferry would give a basis for evaluation of simulation techniques for egress behavior of people on board ships.
- Crowd movement model of simulation on egress behavior of people would be suitable for the condition that passengers are guided by passenger attendances when evacuating.
- Trim and list condition (ship in inclination) and rolling/pitching condition of ships should be taken into consideration when simulation of egress behavior of people is conducted for ships. The data of walking speed and flow coefficient based upon full-scale trials as given in this paper would provide useful information for such simulation.
- Simulation techniques for egress behavior of people in inclined ships should be further developed.

## ACKNOWLIDGEMENT

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Nevertheless, the simulation of these benchmark scenarios are expected to improve ship design by identifying inadequate escape arrangements, congestion points and optimizing evacuation arrangements, thereby significantly enhancing safety. 2 For the above considerations, it is recommended thatÂ  .1 passengers and crew will evacuate via the main escape route towards their assigned assembly station, as referred to in SOLAS regulation II-2/13; .2 passenger load and initial distribution are based on chapter 13 of the FSS CodeÂ  .1 results of full scale trials on similar ships and evacuation systems; .2 results of a simulation based embarkation analysis; or .3 data provided by the manufacturers. However, in this case, the method of. A Simulation Study on Passenger Escape in Rail Tunnels. 2014 / W.L. Wang, T.Y. Jacqueline Lo. Academic research paper on topic "Passenger Ship Evacuation Simulation and Validation by Experimental Data Sets". CrossMark. Available online at www.sciencedirect.com.Â  For safety reasons, IMO has introduced a series of guidelines for undertaking full-scale evacuation analysis and certification of large passenger ships in the design stage.Â  This factor may have significant influence on the evaluation of simulation results especially most tagged passengers arrived in assembly stations with 180 seconds after the sounding of the alarm (Fig. 3). Study on Evaluation of Escape Route by Evacuation Simulation. M. Murayama, T. Itagaki, K. Yoshida. Engineering. 1999. It is important to design effective escape routes in ships and offshore structure which can provide smooth escape of passengers and crew without any congestion and confusion. After the tragedy ofâ€¦ Expand. 19. 1. View via Publisher. Save. On any passenger ships, escape routes are usually pre-designated. Crew members have been trained according to a prepared plan. However, effective escape route arrangements could be changed by evacuees' characters. This evacuation simulation program demonstrates effective escape route options under a range of conditions. We discuss escape route arrangements for aged persons via the evacuation simulation. Discover the world's research. 20+ million members.Â  One way for the evaluation is an evacuation simulation. We are developing an evacuation simulation program to estimate evacuation time and the [Show full abstract] optimal escape route. It uses multi-agent method and can treat evacuees including disabled persons individually. Simulation of Passenger Evacuation Process in Cruise Ships Based on A Multi-Grid Model. by. Min Hu.Â  [15] considered the interplay between passengers and established an evacuation model of passengers in a rolling ship by using a cellular automaton. Yuan et al. [16] presented a simulation method based on a neighborhood particle swarm optimization algorithm, wherein they mainly focused on solving the conflict problem of the shipâ€™s staff in the model. Nevalainen et al. [17] studied from three situations which contained a human response to environmental stimuli in accidents, way finding under an emergency and social environment, and panic, and investigated the human environment interaction during evacuation. Zhu et al.