RESEARCH ON EVACUATION DESIGN: RAILWAY STATION AS AN EXAMPLE

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ABSTRACT

This study is to report the current research at The Hong Kong Polytechnic University, by taking a railway station as an example. Evacuation design is a key element in providing fire safety, especially in determining the means of escape under performance based fire code. The existing evacuation design of a typical station is reviewed first. The details of the station will then be studied. As it is not feasible to perform real fire experiments within the station, computer software was used to simulate different fire scenarios in the station and various evacuation design parameters were studied. The results indicated that the existing evacuation design would be efficient even under densely population. However, the evacuation of the cross-boundary train platform was not successfully completed within 4 minutes, which was the maximum time limit for station evacuation suggested by NFPA 130. Suggestions to the design are presented in the last part of this paper.

1. INTRODUCTION

Local fire safety codes are prescriptive, and taken care of by Buildings Department and Fire Services Department. With the possibility of development of engineering performance based fire codes, research on evacuation is necessary. Being one of the most heavily populated public transportation facilities, Kowloon Station provides railway service for several hundred thousands of people everyday. It is important to have a sophisticated fire safety strategy to protect the passenger in a fire, including accidental and arson fire. In order to develop an effective fire safety strategy for heavily populated facilities, both passive measures and active measures must be considered. Among different passive measures, the design of evacuation path is one of the important aspects and must be considered carefully. For evacuation design, various factors will affect the evacuation performance. This includes the configuration, procedures, environment and human behaviour. Since Kowloon Station is in operation, it is not possible to conduct experiments to study the procedures, environment and human behaviour in a real fire. Due to current limitations, only the configuration factor was studied in detail. The human behaviour could only be studied by observation. The configuration factor includes the occupant load, building layout, number of exits, exit width, travel distance, common path of travel, exit capacity and number of dead end paths. All these parameters would be used to study the total evacuation time of passengers.

Therefore, the main focus of current research is to study the provision of station evacuation. Great effort was spent on assessing the effectiveness of the existing design using computer software and the evacuation performance during peak hours (7:00 am – 10:30 am, 5:00 pm – 8:00 pm). With reference to various standards, site survey and peak hour observations, the effectiveness of the provision of station evacuation was studied. In addition, the feasibility study of various emergency evacuation or egress plans was also included.

2. METHODOLOGY

A code review was conducted as the first step of the current study. Various standards from different countries concerning the escape route design or the provision of means of escape for railway station could be found and the codes for configuration considerations differed from country to country. Discussion on the general requirements would be covered at the later part of this paper.

Then, the next step is to observe the provision of station evacuation with the help of site visits on different stations. Several aspects were considered during the site visits. First of all, the escape route design of the stations was observed carefully. Attention was paid particularly to various parts of the escape route such as exit doors, corridors, escalators, etc. This includes both the number and dimensions.

Secondly, the peak hour occupant load of the station was observed. This is one of the most important parameters in the present study since the effectiveness of the evacuation is highly related to the peak hour occupant load. Moreover, the floor plan of the station was studied because the number and alignment of exit and escalator could be observed easily. Besides the station configuration, the behaviour of passengers on the platform was also observed during the site visit as this is also an important factor in determining the effectiveness of the evacuation design in an emergency situation (e.g. a station fire).

As the station needs to handle a very large occupant load during peak hour, the study of the design is focused on the peak hour. Before having a detailed study on the peak hours, the peak hours should be determined first. Then a series of observation were conducted in the peak hours such as population determination and observation of human behaviour. Finally, computer software was used to study the situation of evacuation of the station.

3. LITERATURE REVIEW

The escape route design in Hong Kong is based on Code of Practice for the Provision of Means of Escape in case of fire (COP) [1] that is published by Buildings Department. As guidance for the design, a set of factors representing usable floor area for different types of buildings is given to determine the population within a building. This factor is presented in the form of metre square per person (m^2 per person). Then, different guidance was given based on the population calculated from this factor. Taking the provision of staircases as an example, different widths of staircase with corresponding discharge value or capacity are given for different stories height of building. Based on the calculated population, the number of staircases with proper width can be defined easily. BS 5588 [2] is another standard concerning the evacuation design. The guidance provided by both documents is similar.

NFPA 130 [3] is the standard that focuses on the fire safety design in a railway or transit station. It covers guidelines for various features in railway stations such as the provision of escalators and gates. It clearly states the dimension and capacity of escalators, exits and gates. The calculation of occupant load of a station is also included in the document. The main focus of the calculation is the 15-minute during the peak hours. Some general requirements of the three standards are listed in Table 1.

Besides standards, models and equations concerning the escape route design and egress time were developed. One of the equations was developed by Pauls [4]. The equation was derived from an empirical method. Pauls started by observing many evacuation drills. Then the aspects of each drill were recorded down carefully. Finally, relations between evacuation time and actual evacuation per meter of effective stair width were developed to describe the actual situation. During the process, Pauls introduced the concept of effective-width of staircase. By observing the relation between the evacuation time (T) (in minute) and population per metre of effective stair width (p), the following equation was derived,

$$T = 0.68 + 0.081\, p^{0.73} \qquad (1)$$

Another equation was derived by a Japanese called Kikuji Togawa [4]. His equation was simplified into another equation,

$$T_e = N_a / B'N' + k_s / v \qquad (2)$$

Table 1: General requirement of standards on escape route design

	NFPA (USA)	COP (HK)	BSI (UK)
Occupant load (m^2/person)	0.65 (concentrated use)	0.5 (public service provided)	5 (office)
Number of exits	Min. 4 for Class A Min. 2 for Class B Min. 2 for Class C	Min. 2	Min. 2
Max. egress time (s)	240	150	150
Max. travelling distance (m)	91.4	30	45
Corridors min. width (m)	1.73	1.5	0.8
Capacity of corridor (person per minute, ppm)	50	---	---
Stairs min. width (m)	1.12	1.5	1
Stopped min. width of escalators (m)	1.22 (two lane capacity) 0.813 (1.5 & 1 lane capacity)	---	---
Slope of ramp	1 in 10 for Class A 1 in 8 for Class B	1 in 12	1 in 12
Ramps min. width (m)	1.73	---	---
Doors & gates min. width (m)	0.914	0.75	0.8
Capacity of door (ppm)	50	---	---

The first component in equation (2) is the flow time. It is obtained by dividing the population (N_a) by the flow capacity which is the width of the most limiting passage way (B') times the mean flow capacity of that passageway (N'). The second component is the travel time for the first person in the evacuation crowd who moves from the point of origin to the destination in which his or her evacuation is considered complete. The travel time is defined by travel distance (k_s) divided by the speed of traveller (v). Equation (2) is used to calculate the minimum evacuation time for buildings where stairs are extensively used.

Another approach to crowd movement calculation developed by a Russian [4] is the use of a density measure based on the ratio of the projected horizontal area of people to the area of walkway. They emphasized modeling and prediction of time in a variety of crowd movement situations,

$$T = t\ (TR;\ STAU) + (n - 1)(TR) / v\ (TR;\ n - 1) + (n - 2) \times dt$$

where t (TR; STAU) is the length of time required for the flow to leave the floor level (n – 1), the term TR is the travel distance on the stairs between adjoining stories, v (TR; n – 1) is the velocity of the flow starting from the congested area at the floor level (n – 1), dt is delay time due to congestion and n is the number of upper floors in the building.

However, the egress time concerned by the above equations is the movement time. Actually, the total egress time should involve pre-movement time (time for perception, time for interpretation, time for action). The pre-movement time is the time delay due to human response to accident. Horasan [6] estimated this time delay in his research work in 1998. The total egress time is actually equal to the sum of pre-movement time and movement time. The Australian 'Fire Engineering Guidelines' was used to find out the pre-movement time in the research. There was another piece of work by Ashe and Shields [7]. Computer software SIMULEX was used in their study. Unannounced evacuations were conducted in a single-storey building and three-storey building. The evacuations were video-recorded and therefore the human behaviour was fully studied. Then, SIMULEX was used to simulate the evacuation of those buildings. Video was used to observe the popular evacuation routes used by evacuees. Then, those routes can be applied into the model to perform the evacuation. This is another approach to study human behaviour.

4. SITE SURVEY

The Kowloon Station is chosen for the current study for the following reasons. Since it is the terminal station of the railway and located at Humg Hom (a congested area in Tsim Sha Tsui East), it needs to cater for heavy passenger flow.

It is a two-level station. The lower level consists of six platforms in which four platforms for domestic trains and two platforms for cross-boundary trains. The upper level is a concourse area that consists of usual facilities, retail shops and catering area, immigration and customs control area for international passengers. There is also an intermediate walkway that links Hung Hom, the station, Tsim Sha Tsui and the cross-harbour bus terminus (Fig. 1).

Fig. 1: Walkway level

There are 17 and 27 exits at the platform level and concourse level respectively. The width of the exits is ranging from 0.85 m to 3.3 m. There are 16 and six escalators available for passengers at the platforms and concourse respectively. The details of the escalators are summarised in Table 2.

Due to the new construction of a circulation area, the fire load of the station may be different from the former Kowloon Station. By grouping the material within the station into plastic, paper, glucose, cotton and wood, the estimated fire load of the platform and concourse will be 2904 MJ and 58275 MJ respectively. The details of the fire load estimation are summarised in Table 3.

An evaluation report [5] of the station evacuation was given as a valuable reference in this research. The escape planning can then be studied more effectively.

Before the evacuation study, the escape routes must be determined. Although the designs of all of the stations are not the same, there may not be great variations in the escape route planning. In general, the normal access route of stations is also treated as the escape route. It is because the access route is designed to handle the large numbers of people during peak hours. Under normal situation, all of the tickets, customs and immigration barriers will be closed. If a fire alarm is sounded, these barriers will be opened to allow people to move away freely.

Table 2: Escalator schedule of the station

Station level	No. of escalators	No. of escalators moving in escape direction	Velocity (ms^{-1})	No. of lifts
Concourse	6	2	0.7	2
Platform 1, 2	8	5	0.7	1
Platform 3, 4	8	5	0.7	1

Table 3: Fire load of the station

Concourse Level			
Material	Mass (kg)	Cal. value (MJ/kg)	Fire load (MJ)
Glucose	500	15.3	7 650
Paper	800	16	12 800
Cotton	50	16.5	825
PVC	500	22	1 100
Wood	1 300	20	26 000
Platform Level			
PVC	132	22	2 904

Moreover, the operation escalators must be taken into account for evacuation planning. All escalators running along the direction of pre-defined exit will be allowed to operate. Other escalators running in opposite direction will be stopped and used as stairs. It is the main idea of the planning for escalators.

Since the Kowloon Station consists of different components, planning can be divided into several parts. In the lower level, there are numbers of escalators provided for passengers to escape from the platform to podium on walkway concourse area. Exits are also provided at the southern platform. Moreover, there are exits provided at the northern end of the platform which lead to open air. In the upper level, large numbers of exits with good visibility are provided for passengers to evacuate from the station. Smoke control is provided at the high roof. Finally, escape from the walkway is not a great problem since the walkway provides excellent visibility to the escape direction. It does not have any fixed fire load too.

5. DETERMINATION OF PEAK HOUR POPULATION

Before having computer simulation on the station, the peak hour population should be determined. The determination starts from locating the peak hour. The determination of the peak hour is based on the population distribution of the exits. Two exits (A & D) were chosen in the estimation since they are the exits that are nearest to the cross-harbour bus stops, HKPU and Tsim Sha Tsui East. The arriving and departing passengers were counted as the population of the exits. Two typical days were chosen for the determination of population (10/12, Exit A & 14/12, Exit D). The time period considered was started from 7:00 to 20:30. By taking the time interval of 30 minutes, the population distribution of the exits is plotted as curves so as to define the peak hour. The combined graph is shown in Fig. 2. By referring to the graph, the peak hour can be defined as two period: morning peak (7:30 to 10:30) and evening peak (17:00 to 20:00).

As there are five exits in the station, ten days were spent on the population determination in which one day was spent on counting the number of arriving passengers and another day was spent on counting the number of departing passengers. Finally, the population of each exit were added together to form the total population of the station during the morning and evening peak. By referring to NFPA 130 [3], the 15 minutes load among peak hour is determined as the population of the station – **3451 persons**, excluding the passengers of cross-boundary trains.

6. COMPUTER SIMULATION – EVACNET4

Since it is not feasible to conduct real fire experiments in the station to study the escape route design, computer software EVACNET4 was used to perform evacuation simulation to study the evacuation time. This software allowed the user to construct his/her own model based on the structure of the building studied. It also allows the user to break down the building into small areas called nodes. Different numbers of occupants can be assigned into the nodes as the initial content and capacity of the nodes. Corridors, staircases and escalators can also be defined as nodes.

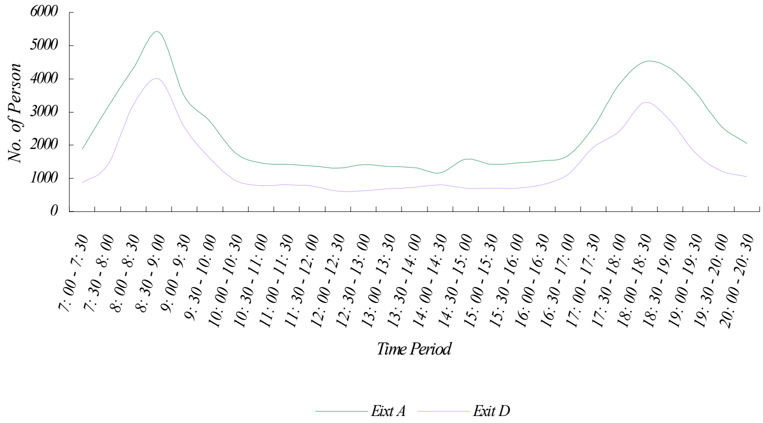

Fig. 2: Daily population of exits A & D

Users can define his/her own escape path by connecting the nodes with arcs. When defining the arcs, two parameters should be assigned: dynamic capacity and time period. They simply represent the travelling speed of people during evacuation. Therefore, the egress time was mainly affected by these two parameters. By the way, the width of corridors or exit doors can also affect the egress time since the determination of the dynamic capacity involves the width of corridors of exit doors. Finally, by linking up the nodes through arcs to destination areas (exit doors) will finish the modification of a building. The user is free to input the maximum allowed evacuation period. As suggested by NFPA 130, 4 minutes is the maximum time period for evacuation.

In this research, the Kowloon Station is defined as a 3-floor building. Platforms and concourse area, escalators and exits are broken down into nodes and named as work place (WP), stairway (SW) and destination (DS) respectively. The determination of the dynamic capacity of arc is based on the formula given by the user manual and the suggestion from the Post-War Building Studies, No. 29 [4]. In the article of 'Movement of People', it was pointed out by Pauls that the report suggested the use of high flows to perform people capacity calculation (40 person per minute per 530 mm or 21 inches of exit width).

- **Validation of the model**

  Before applying fire scenarios into the model, a test case is done first to find out any percentage error of the model. A small zone is chosen for the test that includes one work place, two escalators and one exit. By observation, 463 people require 171 s to leave from the zone. From the simulation of the program, 463 people require 160 s to evacuate from the zone. Under comparison, about **6%** of error exists between the simulation result and the observation.

- **Integration of fire scenarios**

  In order to study the escape route design of the station more effectively, five fire scenarios are integrated into the model. They are:

  - Fire 1: fire at retail area, evacuation of each floor is done independently
  - Fire 2: fire at retail area, people are allowed to escape from platforms to concourse area
  - Fire 3: fire at walkway level, south walkway concourse is blocked
  - Fire 4: fire at walkway level, north walkway concourse is blocked
  - Fire 5: fire at walkway level, both of the walkway concourses are blocked

The result of the simulation is mainly focused on the following areas,

- Total egress time
- Floor clearing time
- Evacuees distribution among exits
- Evacuees distribution among stairways (escalators)
- Effect of smoke generation

Before integrating fire scenarios into the model, a simulation without any fire scenario is done first. Within the evacuation period of 4 minutes suggested by NFPA 130, all of the people in the local train platforms and concourse area can evacuate from the station successfully. However, not all of the people in the cross boundary train platforms can evacuate from the station. 546 persons cannot evacuate successfully. In general, bottleneck occurs at the entrance of each escalator. The floor clearing time of the concourse area is 205 s. These are the general information of the normal case.

7. DISCUSSION

- **Floor clearing time and number of unsuccessful evacuees**

In general, all of the people in the local train platforms can escape from the station within 4 minutes (205 s max) except the people in the cross-boundary train platforms. The following table summarizes the floor clearing time and the number of unsuccessful evacuees of the five scenarios.

The floor clearing time of concourse area of fire 1 is much less than other scenarios since the evacuation is performed independently for the two levels of station. All of the unsuccessful evacuees are located at the cross-boundary train platforms. The number of unsuccessful evacuees is the highest for fire 1 since there are only two escape directions for the cross-boundary train platforms: podium concourse area and exit at north end of platform. Here, the arrangement of the cross-boundary train platforms can be defined as a not very effective design. As there is no any direction of escape except the concourse area and direct exit, evacuation of the platform may cause great problem. The number of escalators available for the platform is not enough such that the evacuation is not successfully completed.

- **Evacuees distribution among exits**

The graph in Fig. 3 shows the distribution of evacuees among exits. There are several critical points generated by the program. The evacuation process mainly falls on the exits located at the front side and back side of the concourse area and also the exits at the walkway level. As those exits are the main escape path for the concourse area, people can locate them and escape from the station easily. The condition of the walkway exits becomes important to the evacuation when the walkway exits are the only way for people to escape from the platform to a safe place.

- **Evacuees distribution among escalators**

From the graph in Fig. 4, the distribution of evacuees among escalators is quite even. Actually, the distribution is mainly influenced by the exits available to evacuees. By the way, the escalators connected to the walkway exits are congested. Other than the two critical points, the number of people using escalators is kept at about 200 since these escalators direct people to the nearest exits.

- **Effect of smoke generation**

Another computer program FPETool is used to simulate the smoke layer development at the concourse area during evacuation. The simulation results of the program are shown in Figs. 5 and 6. The graphs in Fig. 5 and Fig. 6 show the relationship between the smoke layer depth and the room temperature to time respectively. By considering that the time is equal to 240 s (4 min), the smoke layer depth is about 0.75 m. When focusing on the room temperature, it is about 42 °C. Since the area of the concourse area is quite large (about 150 m × 100 m), the effect of accumulation of smoke is not so obvious. When considering the room temperature, the effect is also not very serious. Since when the time is equal to 205 s which is the floor clearing time of concourse area, the room temperature is about 35 °C.

Table 4: Egress time of fire scenarios

Floor clearing time of concourse area / s				
Fire 1	Fire 2	Fire 3	Fire 4	Fire 5
185	205	205	205	205
Fire 1	Fire 2	Fire 3	Fire 4	Fire 5
1460	546	546	546	546

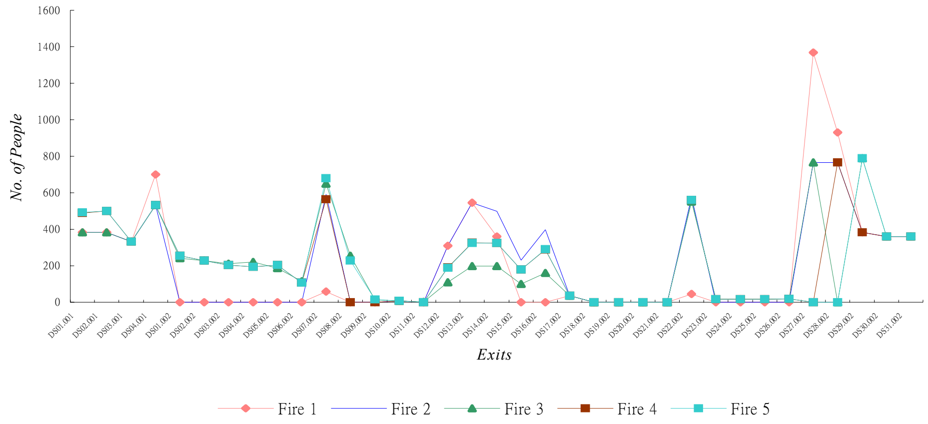

Fig. 3: Distribution of evacuees among exits

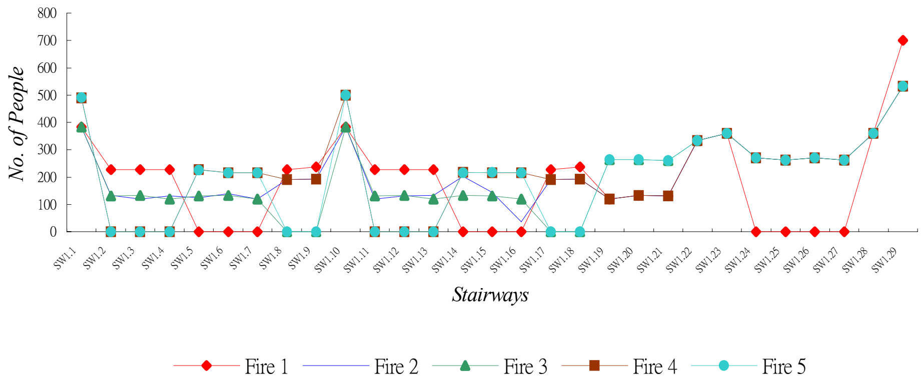

Fig. 4: Distribution of evacuees among escalators

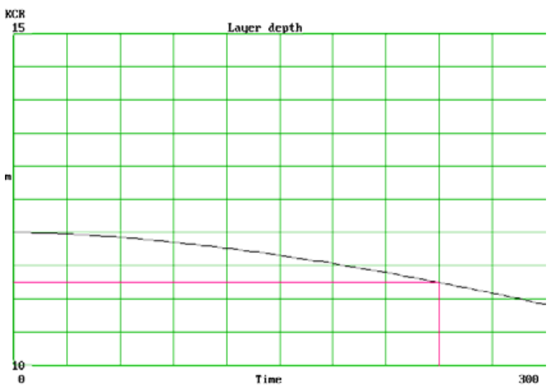

Fig. 5: Smoke layer depth against time

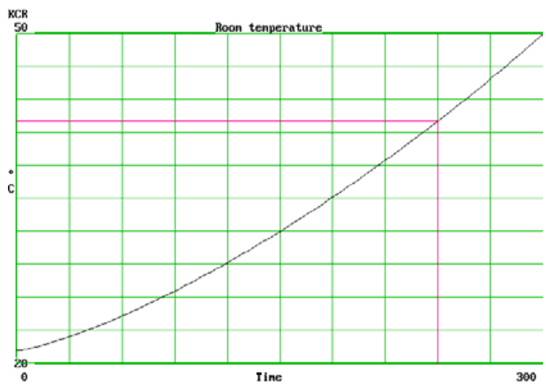

Fig. 6: Room temperature against time

8. RECOMMENDATIONS

As suggested by Horasan [6], the total evacuation time can be decreased by using large exit or directional signs. It is a good idea for the people who are not familiar with the building. But for the case of railway station, this may not be very effective. Since the population is a mixture of frequent users and passengers who are not familiar with the station, simply enlarging the exits and adding the directional signs may not be an effective method. Some of passengers that are very familiar with the station may choose their usual exits. These may cause confusion in a fire scenario. A fire safety management plan is very important.

Alternative means for evacuation in the platform other than the escalators must be considered.

Since the station consists of platform and concourse area, the emergency plan for these areas may not be the same. Good coordination of evacuation in the platform and the concourse area must be considered.

9. CONCLUSION

When considering the evacuation of railway stations, not only the provision of exit signs should be considered, alternative means of escape must be considered. As people use the railway services everyday, they know the station well. They may use escalators for evacuation. For platform evacuation, if the fire source is near the escalator, the escalator may not be appropriate for the passengers to evacuate. As the escape direction of the platform is just the northern exit and the concourse area, alternative means for egress are needed.

In general, this study demonstrates the idea of engineering approach on design. Traditionally, the escape route design of buildings is based on the suggestion from COP [1]. However, this is not a feasible approach for buildings with innovative design. For buildings with irregular designed floor plan, the number of staircases suggested by COP may not be able to meet the actual demand. Additional exits will be required for some dead end areas. This idea can be reflected from the simulation results. Therefore, when considering the escape route design of buildings, designers may combine the suggestion from COP and the actual demand reflected from the building configuration. Then the effectiveness of the design can be improved significantly.

Although five fire scenarios are integrated into the models, there are still some drawbacks. The main drawback is that the model used, EVACNET 4, cannot study the effect of human behaviour, crowd behaviour in the evacuation process. Therefore, the basic assumption of the simulation is that people are not in a panic situation and able to find the correct escape path.

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Q & A

Q1: You mentioned that about 500 people failed to evacuate. What are your criteria to determine whether the evacuation is successful or failed?

Dr. Fong: We used the EVACNET4 software to define nodes and arcs in the station. Then, we input the maximum number of occupants collected from our survey and other parameters to calculate how many people will evacuate from the station and counted the number who succeeded in evacuating from the station. We found that 500 people could not evacuate within four minutes. In NFPA 130 for railway stations, 240 s is specified as the maximum egress time. This is defined as the time criterion in our simulation.

Q2: So, basically your criterion is four minutes. If people can evacuate from the platform station or whatever within four minutes, that means successful, otherwise, fail. How would this figure match with the MoE and MoA codes issued by the Buildings Department?

Dr. Fong: We carried out a survey on regulations. We consider that the criterion of evacuation time 150 s is much longer than the actual time required for evacuation.

Q3: Are there any justifications for extending the time from 150 s to say 240 s?

Dr. Fong: No. For this one, we haven't considered any comparison.

Q4: (1) How do you deal with the pre-movement time of people before evacuation? You did not consider this in your simulation. This is very important and the pre-movement time may be very long which can be longer than 240 s. How do you deal with that? (2) I think that you should consider the pre-movement time but not only the evacuation time. (3) If the simulated time in EVACNET 4 is shorter than the actual evacuation time. How do you deal with that?

Dr. Fong: (1) Yes, you are right. We need to consider the pre-movement time in evacuation. That means how people will perceive the fire alarm and how they will interpret the alarm; after interpreting it is a fire alarm, how they will take action to choose the exit. But, we cannot do it here and we just added a factor, say one minute for people to take action. So, I pointed out in my presentation that using exit signs only may not be sufficient. We need to have a better safety management plan to improve the evacuation. (2) In the railway station, there are different types of occupants. Some of them may be frequent travellers and use the station everyday. They might be very familiar with the station. Some may be tourists and it is the first time they use the station. It is difficult to define the pre-movement time of different occupants in such facility. So, we would encourage the railway station people to implement fire safety management plan such that when there is emergency, it can help to direct the occupants to the safe escape route. (3) Actually, we do not know the actual evacuation time.

Prof. Chow: We should ask ourselves why we still use this kind of evacuation software developed in the UK, USA, Japan and New Zealand without local psychological data. The idea is to take a look at the relative evacuation time. We can try different evacuation scenarios including MoE and evacuation path in certain software and make comparisons between different scenarios. The pre-determined time or the action time is a series of time components which is difficult to quantify without in-depth consideration of the psychological effects. But, even though we do not have those data, we still need to do something as the first step. So, we assume everybody move when an alarm sounds and then we can calculate the evacuation time. We neglect the assumptions made in the evacuation software. Of course, there is psychological data put inside. But, those were determined in the UK, USA, Japan and New Zealand, not in Hong Kong or in China. Even so, we can still take the results as reference values and try different types of evacuation design, different MoE, MoA and then see how many people or percentage of transient occupants (in this case, 500 out of 5,000, i.e. 10 %) did not satisfy the failing criteria. So, we can do something to boost up the percentage such that the occupants can evacuate in time. At the moment, we do not have a good software which takes both physical and psychological effects into account. But we still need to do something and this is the reason why we try this kind of calculation. The argument is not in this kind of evacuation time but why four minutes is defined.

Q5: I agree that the criterion on safe egress time should be set longer than four minutes. We need to consider the fire size, fire scenarios and smoke interface height, etc.

Dr. Fong: I agree with you that in the current study, we only considered the criteria in the regulations and used it as the failing criteria in our simulation.

Q6: You mentioned that human behaviour is a key factor in evacuation. How did you consider this in your simulation?

Dr. Fong: We have not carried out an in-depth study on human behaviour in this project. In other projects, we tried to use videos to monitor how people choose paths and use questionnaires to see how they pick out those exits in emergency. That is what we are trying to do and develop.

Q7: In your conclusion, you mentioned that even if the evacuation design complies with the regulation, successful evacuation may not be accomplished in some fire scenarios. Can you give some examples on that?

Dr. Fong: From the simulation results of egress time, we considered five fire scenarios. In case 2, the number of unsuccessful evacuees is much higher than in other scenarios.