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Numerical Studies on Evacuation for Supertall Commercial Buildings

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Abstract

Long evacuation time during emergency for offices in supertall commercial buildings is a deep concern and was discussed in this paper. Different codes and regulations for safe egress were reviewed. A building of fixed floor area but heights varying up to 500 m was taken as an example. The required total evacuation times for selected offices in this building were estimated by four different empirical expressions. The height, population density and stair width of the supertall building were varied during the calculation. The estimated evacuation times were justified with reference to the local codes on means of escape. Even with a lower population density of 4.5 persons per square meter, which is only half of the allowed value specified in the Hong Kong code, the estimated minimum total evacuation time was 26.9 min. The evacuation time for a supertall commercial building with high occupant loading is very long. Evacuation by elevator is recommended to be an alternative. Safe evacuation strategy for supertall buildings should therefore be watched carefully.

Keywords: evacuation time, supertall building, occupant loading, stair width

1. Introduction

Hong Kong changed from an industrial city to a big international financial centre in the past three decades. Instead of working in manufacturing plants, most of the employees in Hong Kong are working in offices now. Safety at non-industrial workplaces like offices, especially those in supertall buildings, is a concern. According to the Council on Tall Buildings and Urban Habitat [1], a supertall building is taken to be of height over 984 feet or 300 m. Evacuation has been identified as a key fire safety concern of supertall buildings [2]. Occupants are supposed to leave the fire room to a safe place with minimum injuries and life loss [3]. The fire codes on safe egress are frequently updated. Taking Hong Kong as an example, codes [4,5] specifying minimum requirements on hardware fire safety provisions had been changed several times since 1972. Offices in various types of buildings with different heights and ages would have very different egress problems during emergency. For example, most of the buildings constructed before 1972 have only one staircase. The flat inside used to be partitioned into smaller rooms by timber products without fire retardant. Escape routes in existing buildings should be evaluated carefully.

Evacuation time for offices in a supertall commercial building was studied in this paper. Code requirements on ensuring evacuation of occupants to a safe place through the protected corridor, passageways or lobbies within a certain period of time were reviewed. Some key parameters in Hong Kong codes are adopted from UK practices. Examples [6] are the nominal clearing time of 2.5 min for non-sprinklered buildings and 5 min for sprinklered buildings, and the discharge rate of 40 persons per minute per 500 mm exit width. Adequacy of such code for fire safety was discussed. Problems identified on evacuation were studied using empirical equations as reviewed

[7-9]. This study extended the previous projects [10] on evacuation times by empirical expressions for offices in five tall buildings including a community building, a university campus, a commercial building, a bank and a residential building.

The data of the commercial building plan were taken out from that earlier survey [10]. The height of the building was varied as 100 m, 200 m, 300 m, 400 m and 500 m to investigate changes in evacuation time with height of the supertall building. The population density and the stair width of the building were also varied within the range specified in the standard requirements with reference to the local codes. Sensitivity studies on the predicted evacuation time of the different empirical expressions by varying the stair width and population density of the building were carried out.

Requirements for emergency evacuation in offices with reference to the regulations in Hong Kong [4,5] were compared with those in the United States [3] and Australia [11]. The code of practice for Means of Escape (MoE) and Means of Access (MoA) [4,5] in Hong Kong, National Fire Protection Association – Life Safety Code [3] in the United States, and the Building Code of Australia [11] in 1990 were taken as the references.

2. Local Code Review

In Hong Kong, the MoE code [4] should be followed to provide adequate escape routes in fire and other emergencies. The MoA code [5] is developed to assist in firefighting and rescuing in buildings by ensuring adequate access for firefighting personnel in buildings in the event of fire and other emergencies. Prescribed figures are imposed for building designers to determine the occupant density of building, number of exit doors, width of stairways, discharge values, and others.

Key requirements described in the MoE code [4] are:

- Occupancy density of office building is 9 m^2 per person (or 1/9 persons/m^2)
- Physical requirements of escape route include specifying clear height, smoke lobby, and other escape route illumination requirements.
- There should be adequate exits for safe egress.
- Maximum travel distance of exit routes at each storey is specified.

The discharge values for simultaneous evacuation of all floors should be based on the following:

- Escape strategy is based on the total evacuation of the building.
- Evacuation from a protected area should be completed within a notional period of 150 s (2.5 min) for non-sprinklered buildings and 300 s (5 min) for sprinklered buildings.
- Flow rate of people in descending the staircase is taken to be 80 persons/m width/min.
- Number of people temporarily housed in the staircases during evacuation is taken to be 3.5

to 3.9 persons/m^2.

Requirements in Hong Kong are compared with others [3,11] as shown in Table 1. The maximum value of travel distance is 36 m, shorter than the value of 61 m (but allowed to be 76 m for buildings fully covered by sprinkler) in NFPA 101 of USA [3]. Note that only a very short distance of 20 m is specified in the Australian building code [11]. There is no limit on the travel distance for having two travel paths to the exits.

3. Empirical Expressions for Estimation of Evacuation Times

There are many methods for calculating the evacuation time as reviewed recently [7,8]. The total evacuation time from the starting point of movement to a safe place can be estimated by empirical equations.

Crowd movement is normally studied by using three fundamental parameters [12]. These are the density D (in person m^{-2}) of occupants, travel speed S (in ms^{-1}) and the escape route width W (in m). Values of these three parameters are related to the number of fire escape exits, the width of the exit door and the maximum travel distance in the building design. Based on fundamental traffic equations, these three parameters would give the number of people passing through some reference points in a unit time referred to as the flow f (in number of person s^{-1}):

$$f = S \cdot D \cdot W \qquad (1)$$

In addition, according to the study by Nelson [13], with the hydraulic flow calculation, S is related to D by a constant k ranging from 0.54 to 3.8 persons per m^2, and multiply constant a with value 0.266 as:

$$S = k - akD \qquad (2)$$

This method by Nelson is rather complicated [13].

Four of the empirical methods including the one by Pauls [12,16], the equation derived by Togawa [17], the Russian Methods by Predtechenski and Milinski [14] or Kendik [15] and the method by Nelson [13] will be used in this paper. All these equations are summarized below:

3.1 Equation by Pauls (1980)

The minimum evacuation time T (in min) by stairs calculated from the simplified linear equation derived by Pauls [12] is:

$$T=2.00+0.0117p \tag{3}$$

In the above equation, p is the actual evacuation population per meter of effective stair width.

Note that the above equation [16] has the upper limit of 800 persons per meter of effective stair width. For buildings with more than 800 persons per meter of effective stair width, times for uncontrolled total evacuations in tall buildings can be predicted by:

$$T=0.70+0.0133p \tag{4}$$

3.2 Russian method by Predtechenski and Milinski (1969) or Kendik (1985)

The mathematical method of Predtechenski and Milinski [14] or Kendik [15] assesses the movement of an egress population on a horizontal or sloping escape route simultaneously based on the density of population.

The ratio between the sum of the person's perpendicular projected areas and the available floor area for the flow d (in m^{-2}/m^{-2}) is defined as:

$$d = \frac{Pf}{bl_{strom}} \tag{5}$$

In the above equation, l_{strom} is the length of crowd flow, f is the perpendicular projected area of a person, and b the width of crowd flow as well as the width of the escape route. Note that the maximum value of d is 0.92.

The specific flow q is given by the function of flow density d and flow velocity v:

$$q = dv \tag{6}$$

The time T_F required for the last person to reach the access door to the staircase is:

$$T_F = l_F / v_F \tag{7}$$

The time T_{TR},n taken by the first person from the top floor (the nth floor) to arrive at the adjoining storey is:

$$T_{TR,n} = l_{TR} / v_{TR;n} \tag{8}$$

If $T_F < T_{TR}$, the total evacuation time T_{tot} is:

$$T_{tot} = T_F + nT_{TR;n} \tag{9}$$

If $T_F > T_{TR}$, and the geometric configurations of all the upper storeys are identical, the total evacuation time T_{tot} is:

$$T_{tot} = T_F + n\frac{l_{TR}}{v_{TR;n}} + m\Delta T \tag{10}$$

In the above equation, n is the upper number of the floors, l_{TR} is the average travel distance on the stairs between adjoining floors, $v_{TR;\,n}$ is the flow velocity on the stairs at a density d_{TR}; m is the number of patterns of higher density and ΔT is the delay time due to a flow population of increased density. The factor m can be determined by iteration.

The delay time ΔT due to a flow population of increased density can be given by:

$$\Delta T = \frac{v^{'}(T_F - T_{TR})(v_{TR;n} - v_{TR;(n-1)})}{(v_{TR;(n-1)} - v^{'})v_{TR;n}} \tag{11}$$

If there is congestion in the direction of escape occurs, the time for total evacuation T_{tot} of a building is described by:

$$T_{tot} = T_{TR;STAU} + (n-1)\frac{l_{TR}}{v_{TR;(n-1)}} + (n-2)\Delta T \qquad (12)$$

In the above equation, $T_{TR;\,STAU}$ is the time required for the flow to pass the floor level (n-1); $l_{TR}/v_{TR;(n-1)}$ is the travel time of an evacuee, coming from the overcrowded area at floor level (n-1), arriving at the adjoining storey without any delay due to congestion; ΔT is the delay time due to congestion of escape routes, repeating on each floor level.

3.3 Togawa equation (1955)

A simplified equation for calculating evacuation time consisting of flow time and travel time of the first person of the crowd to the safe place is derived by Togawa [17].

$$T_{tot} = Na/BN + K_s/V \qquad (13)$$

In the above equation, T_{tot} is the total evacuation time (in s), Na is the total number of escaping people (in persons), B is the breadth of the most limiting passageway (in m), N is the unit flow capacity of the most limiting passageway (in persons/m/s), K_s is the travel distance for the first person in the crowd to the exit (in m), and V is the walking speed of the crowd (in m/s).

3.4 Nelson equation (1990)

Specific flow, Fs, which expresses the flow of evacuating persons passing a point in the exit route per unit of time per unit of effective width, is defined [13] as:

$$Fs=SD \tag{14}$$

In the above equation, D is the density and S is the speed of movement as in equation (1) above. Combining the above equation yields:

$$Fs=(1- aD)kD \tag{15}$$

The predicted flow rate of persons Fc passing a particular point in an exit route is given in terms of the effective width We of the route:

$$Fc =FsWe \tag{16}$$

The time t_p for a group of persons to pass a point in an exit route can be expressed in terms of the population P in units of persons as:

$$t_p = \frac{P}{(1-aD)kDW_e} \tag{17}$$

4. Case Studies

Offices in a commercial building were studied in this paper. The actual area of each floor is 475 m^2 and the population for each floor is 45. The four methods [12-17] discussed in above were used to study the evacuation times for offices in the supertall building. Occupants were assumed to start egress at the same time for all cases. Height of the building was varied as 100 m, 200 m, 300 m, 400 m and 500 m to investigate changes in evacuation time with height of supertall building.

The population and the stair width of the building were varied within the range specified in the standard requirements of the local codes. Population Na in offices calculated from the allowed occupant loading (9 m^2 per person) in the MoE code in Hong Kong [4] is approximately 52 persons per floor in this case. Additional lower value of 0.5 Na was calculated by each method [12-17]. Results on evacuation time under density Na are shown in Fig. 1a to 1d.

On the stair width, the minimum limit of 0.85 m and maximum limit of 1.8 m were taken to compare with the actual width of 1.2 m. Results on evacuation time with different stair widths are shown in Fig. 2a to 2d.

5. Discussion

Changes in evacuation time with height at different floor levels are shown in Fig. 3. Evacuation time for floors at higher levels would be longer. As observed, results by equations of Pauls [12] and Togawa [17] were shorter than those by the Nelson method [13] and the Russian method [14,15] as shown in Fig. 3. Evacuation time estimated by the Russian method gave a sudden increase in value with the increasing height. Note that this method emphasized merging activities, including congestion and queuing in the staircase.

With actual population and stair width specified in the MoE code [4], total evacuation time for the building of height 100 m predicted by the Pauls method [12] was 15.7 min. For the building height exceeding 300 m, the evacuation time was 46.1 min.

When the population density varied as 0.5 Na and Na, the increasing trend of the evacuation time can be obtained by all four methods [12-17]. As shown in Fig. 1d, the rapid increase in evacuation time with the population density of Na by the Nelson method [13] indicated that flow time affected by population density is a sensitive key factor in this equation. Under normal occupant loading allowed in MoE code [4], evacuation in a 100 m and a 300 m tall building would take at least 18 min and 53 min respectively.

The stair width of the building was also varied within the range specified in the standard requirements with reference to the local code [4]. Widening the staircase width from 0.85 m to 1.8 m would change the evacuation time significantly predicted by all the methods [12-17], assuming that the stairs to be used and the widths of all exits are identical. Note that the estimated optimal evacuation time was 31 min for the building of height of 300 m by the Pauls method [12]. In other cases, using minimum 0.85 m staircase width in the codes would give very long evacuation time. These long values should be watched carefully for safe egress.

6. Conclusions

Evacuation for offices in a supertall commercial building was studied in this paper. Empirical equations [12-17] available in the literature were used and compared. Assumptions and simplifications made in those equations derived from empirical methods might not hold for supertall buildings. Data compiled from fire drills might not be applicable in justifying the empirical methods. Even if the evacuation design was based on specification in local regulations or codes such as the MoE code in Hong Kong [4], the evacuation time would be very long. This point should be watched for future design of evacuation routes for supertall buildings.

Without providing adequate number of escape routes, it is difficult to rely only on fire safety management to reduce the long evacuation time. Local citizens are not likely to have good practices in keeping order during emergency. This was clearly demonstrated by the Lan Kwai Fong incident in 1993 [18]. It is impossible to implement practicing overseas standards in Hong Kong, such as adopting long travel distance up to 76 m in USA [3]. Occasional visitors who are not familiar with the office environment would get long waiting time [19-23]. Fire drill in the fire safety plan can only allow longer-term residents to get more familiar with the evacuation route. Bearing in mind that under normal occupant loading allowed in the MoE code, evacuation in a 300 m tall building would take at least 53 minutes as shown in the above calculations. Additional evacuation routes cannot be provided easily for existing supertall buildings.

Evacuation strategy for supertall buildings should be watched carefully. Using elevators would shorten the evacuation time [24], but adequate fire protection must be provided for the elevator car, lift shaft and lobbies. Designing fire safe elevators will be an effective evacuation means.

However, the elevator design must be safe under big fires and supported by full-scale burning tests [24].

7. Additional Comments

The paper was published as a journal paper [25]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [26-53].

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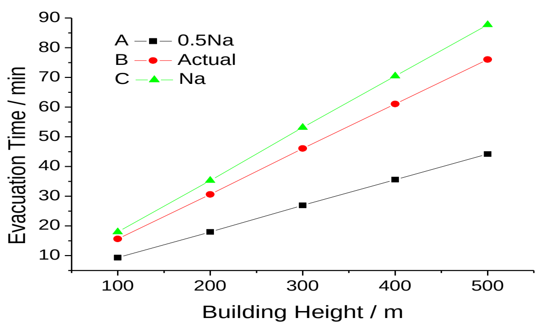
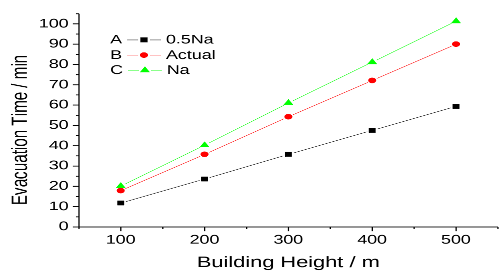
A441UL22-1d (opened 25 June 2023)
A441UL22-1e (opened 30 June 2023)
A441UL22-1f (opened 3 July 2023)

Table 1. Different design standard requirements

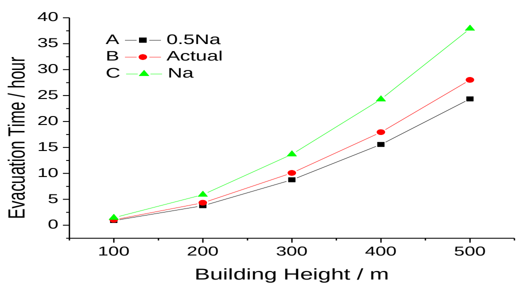
	Building code of Australia (1990)	NFPA 101(2002) in United States	MoE and MoA codes (1996) in Hong Kong
Exit doorway width / m	0.75	0.81	0.85
Distance between 2 alternative exits / m	9	half of the length of maximum overall diagonal dimension of the area served	6
Exit route width / m	1 + 0.25 for each 25 persons in excess of 100 persons	0.91	1.05
Staircase width W / m	Exit doorway width < W	Exit doorway width < W	Exit doorway width < W < 1.8 m



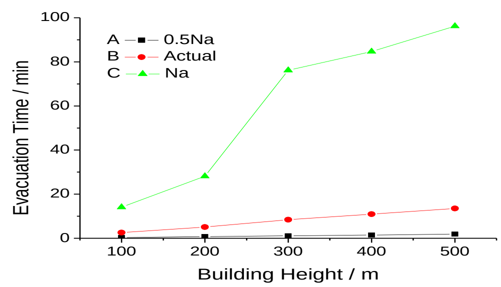
(a) Pauls equation (1980)



(b) Togawa equation (1955)

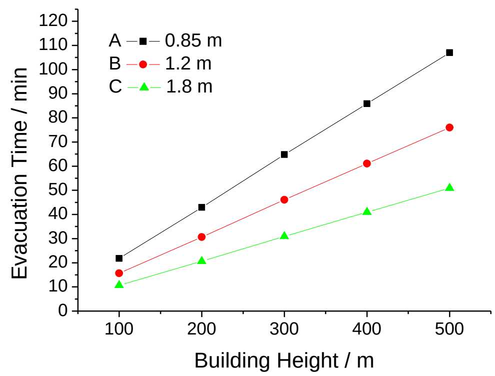


(c) Russian equation (1978)

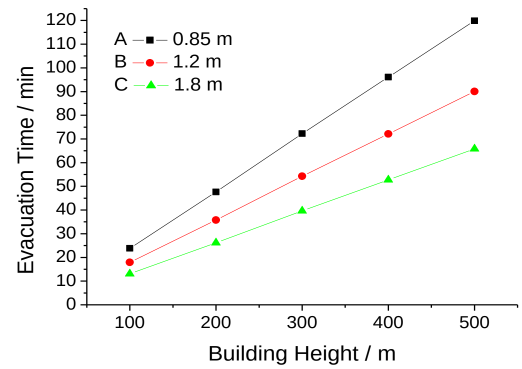


(d) Nelson equation (1990)

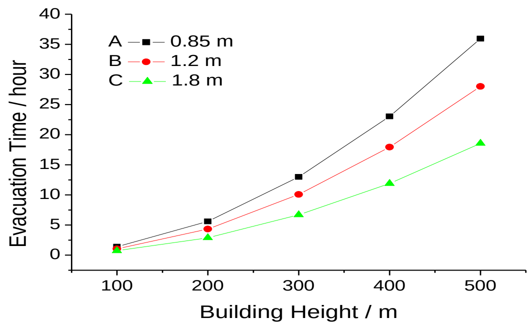
Fig. 1. Effect of population



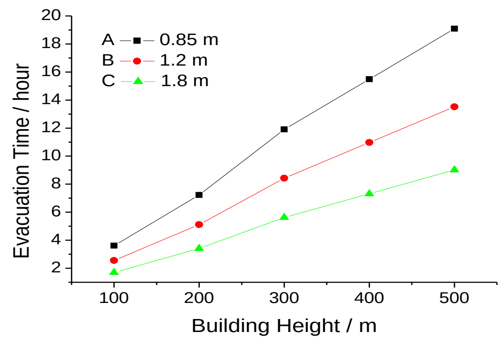
(a) Pauls equation (1980)



(b) Togawa equation (1955)



(c) Russian equation (1978)



(d) Nelson equation (1990)

Fig. 2. Effect of stair width

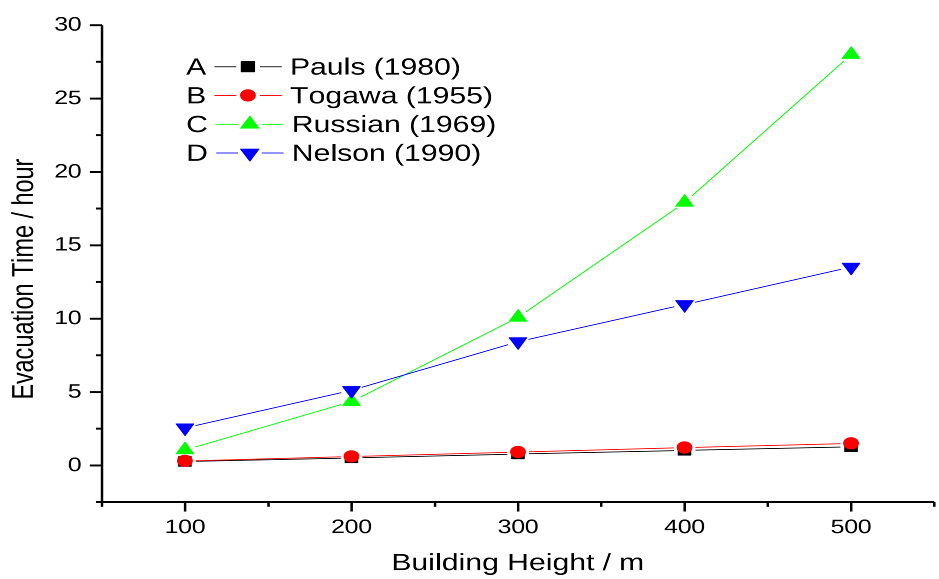


Fig. 3. Evacuation times by different methods