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The effect of PSD on life safety in subway station fire [†]

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Abstract

Fire is a major risk in the event of subway station fire due to the confining geometry of the underground space. As a part of an effort to improve the life safety in subway fire, the platform screen door (PSD) is more and more installed on the ground that PSD provides many benefits to passenger's safety. This paper not only performs fire simulation and evacuation modeling but also estimates the effect of PSD on passenger's life safety and an evacuation measure in the event of a subway station fire. The Fire Dynamics Simulator (FDS V406) code is used to predict smoke spread and the time available for evacuation during the fire. The time required for evacuation is obtained from simple travel time relationship from Nelson and MacLennan. The passengers in platform with PSD have more available time of about 100s than in case without PSD. The subway turnstiles (ticket gate) dramatically increase the time required for evacuation due to jam and bring on danger passenger's life safety. Therefore, the passage without barriers like turnstiles will be required not to obstruct evacuation for passengers in an emergency case of subway fire.

Keywords: Available safe egress time (ASET); Life safety; Platform screen door (PSD); Required safe egress time (RSET); Subway station fire

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1. Introduction

Due to the confining geometry of the underground space, fire is a major risk in the event of subway station or metro tunnel fire. When a fire occurs in subway station, the most hazardous factor is not flame and high temperature but toxic gas. These large quantities of smoke are likely to spread rapidly to station platform and along the ceiling of tunnel due to confinement of the tunnel wall and will reduce visibility. It becomes an obstacle to fire extinction and can cause fatalities by asphyxiation. On 18 February 2003, as an example, a subway train was set on fire with gasoline by a mentally ill patient at Jungangno Station in Daegu, South Korea. The fire quickly spread to all six coaches of the train within 2 minutes due to the highly flammable interior of the train, destroying two trains and causing large casualties of 192 deaths and 148 injuries. The reasons for many casualties are as follows [1, 2];

- The interior materials include the seats, flooring and advertisement boards were not made of fire proof materials but composed of flammable fiberglass, carbonated vinyl and polyethylene.
- No adequate smoke control system was operated although much poisonous smoke products due to fire spread to another train.

This accident underscored the importance of fire safety engineering in underground space and the need of enhancement in smoke control system in order to maintain a safe evacuation path that is free of smoke and toxic gases. After this tragedy, the Korean government determined to improve the fire safety to all subway systems. As part of an effort to improve the life safety in subway fire, platform screen door (PSD) systems are installed in main subway station. The PSD system plays a role of not only prevention of smoke spread but also safe boarding the subway. Therefore, the PSD system for subway stations is more and more installed. However, even though many researches have been carried out to predict smoke behavior or movement and related topics in underground space such as tunnel [3-6] and subway system [7-9], the effect of PSD on passenger's life safety in the event of a subway fire had rarely been conducted. This paper not only performs fire simulation and evacuation modeling but also estimates the effect of PSD on passenger's life safety and an evacuation measure in the event of a subway station fire. The Fire Dynamics Simulator (FDS V406) code is used to predict smoke spread and the time available for evacuation during the fire. The time required for evacuation is obtained from simple travel time relationship from Nelson and MacLennan [10].

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2. Subway platform geometry and fire scenario

The subway station chosen for present study is assumed to represent a typical subway station with three stories below the ground, 220 m long × 15 m high × 24 m wide as shown in Fig. 1. The subway station is modeled for simplicity but is representing a type of subway station. For simplicity, no vertical gradient along a platform is assumed. There are six exits to ground (safe region), 5 m wide × 3 m high in Basement 1 and subway turnstiles (ticket gate) in Basement 2, which are mechanical barrier and have metal arms that passengers should push round as passengers go through them to evacuate to safe region. The other characteristics of the subway station and train are as follows:

- Number of carriages: 10 carriages.
- Length: 19.5 m, width: 3.12 m, height: 4 m per carriage.
- Number of passengers: 240 persons per carriage.
- Number of subway train door: four doors with 5 m apart per carriage.
- Width of subway train door: 1.3 m.
- Number of turnstiles: 15.
- Width of turnstile: 1 m.

The fire scenarios used in this study is chosen deterministically. A subway train catches fire at the middle of subway in previous subway station, which breaks out outside a carriage. It is highly likely that an exterior fire has a high probability of occurrence and causes the greatest hazard in a train fire. The incident subway departures for next subway station with unawareness of fire. The fire develops and is detected all the while the train is running. Finally, subway driver notifies emergency to all passengers before train arrives at the next station. Once train arrives at next station, when fire grows further for 2 min (generally, it takes subway train 2 min to arrive at next station in Seoul), all passengers start to evacuate from subway train to exit to ground.

3. Fire modeling

3.1 Numerical method

In order to estimate the effect of PSD on the life safety of passengers, simulations of smoke spread in case of subway station fire are carried out using FDS V406 code, developed by National Institute of Standards and Technology (NIST). The FDS code describes fire-driven flows using LES turbulence model, the mixture fraction combustion model, finite volume method of radiation transport for a non-scattering gray gas, and conjugate heat transfer between wall and smoke flow. The governing equations for FDS code can be found in McGrattan and Forney [11] and McGrattan [12].

Fire size is based on the Heat Release Rate (HRR) measurement of a burning coach [13]. The HRR increases to 35 MW within 5 minutes after fire occur and decreases after 9 minutes. The HRR curve in Fig. 2 is the design fire used as input parameter in FDS calculation. In the fire simulation, the values of HRR from 2 min to 17 min after ignition are used according to fire scenario.

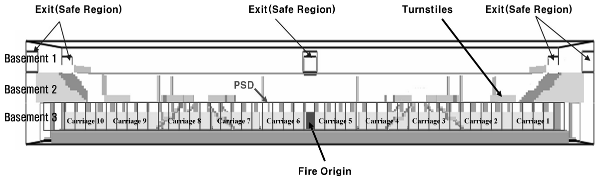

Fig. 1. The geometry of subway station (not to scale).

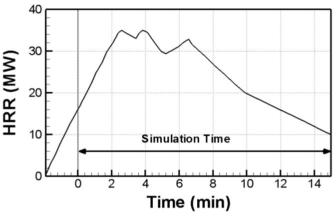

Fig. 2. HRR curve used in fire simulation.

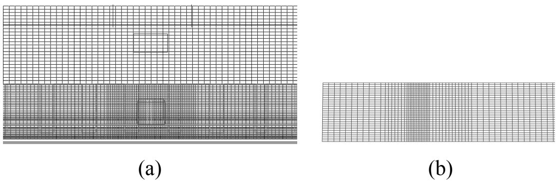
(a) (b)

Fig. 3. Grids distribution used in numerical simulations. (a) longitudinal grid distribution near fire source (b) Cross-sectional grids distribution.

3.2 Grid system

Fig. 3 shows the longitudinal grid distribution near fire source in Basement 1-3 and cross-sectional grids in Basement 3 used in the present fire simulations. Because grid size in LES code is directly concerned with filter width, grid spacing is very important to simulate fire driven flow. In order to get proper numerical grid spacing, grid independent tests are carried out for different grid spacing. Table 1 shows the grid sensitive test conditions. The grid sensitive test measures how long smoke takes to reach Basement 2 because the numerical simulation is mainly focused on smoke or soot spread in subway station. Based on the results of grid sensitive test, the mesh of 1,059,840 cells is used. The grid cells in Basement 3 are non-uniform in x and y directions and uniform in z direction. On the other hand, all cells in Basement 2 and 1 are uniform in size in three directions. Since the accuracy in Large Eddy Simulation (LES) increases as the number of grids increase, finer grids are used near fire source to resolve fire adequately. With regard to computing time, this is less than 350 h by IBM, Pentium D 3.4 GHZ.

3.3 Boundary conditions

Atmospheric boundary conditions are applied at both ends

Table 1. Grid sensitive test conditions.

Case	Number of grid (Basement 3, 2, 1)	Grid Space near fire (x, y, z)	Total grid number	Time to reach Basement 2 (s)
A	240 x 36 x 20 240 x 32 x 9 240 x 32 x 9	0.30,0.27,0.3	311,040	273
B	270 x 45 x 24 240 x 36 x 12 240 x 36 x 12	0.27,0.22,0.25	498,960	293
C	360 x 45 x 27 320 x 36 x 12 320 x 36 x 12	0.20,0.22,0.22	713,880	307
D	360 x 60 x 32 320 x 48 x 12 320 x 48 x 12	0.20,0.16,0.19	1,059,840	315
E	450 x 60 x 36 320 x 48 x 12 320 x 48 x 12	0.16,0.16,0.17	1,340,640	318
F	500 x 64 x 36 360 x 40 x 12 360 x 40 x 12	0.15,0.15,0.17	1,497,600	320

of the tunnel in basement 3 and six exits to the ground in basement 1. The PSD is assumed tempered glass and broken to piece when its surface temperature is over 250℃. The opening of PSD may lead to dramatic changes in smoke spread. Also, the smoke yield is assumed to 8 % of the fuel, which is converted from the fraction of fuel mass. The fuel used in fire simulation is comprised of several materials including polyethylene, polypropylene, nylon, polyester, and polyurethane. These materials' soot yield can be seen reference [14].

4. Evacuation simulation

Passenger's life safety depends on whether passengers can evacuate safely before untenable conditions occur. Generally, the time required to egress called RSET consists of detection time, response time and movement time. Detection time is the time from fire ignition to fire detection. The response time is defined as the time from the alarm sounding until the passenger initiates movement to evacuate the subway station, a measurement on how long it takes passengers to react and begin to evacuate the subway after fire detection. The summation of detection time and response time is called pre-movement time. So to speak more exactly, the pre-movement time is defined as the time before the occupants start to travel to exits. Finally, movement time is the time taken for passenger to evacuate the subway station. In present evacuation simulation, there is no pre-movement time but only movement time because all passengers wait until the train arrives at next station and then start evacuation simultaneously as soon as train door open in next station as mentioned in fire scenario above. The movement time depends on the number of available exits, their width, evacuation path and the number of passenger in subway.

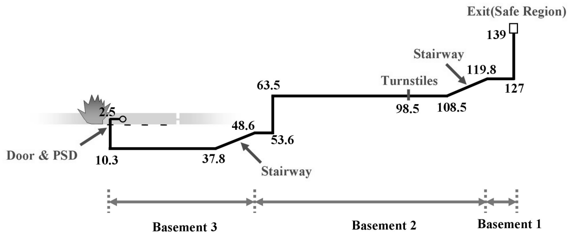

Fig. 4. Evacuation path.

The average number of passengers per carriage is assumed 240 persons. The number of passengers is estimated from averaged degree of congestion from the No. 1-8 subway line in Seoul metro systems, which is an indicator of the crowdedness in traffic system. The width of subway train door is 1.3 m. The main evacuation path consists of subway door, platform and stairway in Basement 3, Basement 2, subway turnstile, stairway in Basement 2, Basement 1 and exit to safe region as shown in Fig. 4. The numeric values in Fig. 4 represent escape distance from initial location of passenger and width of path, respectively. Evacuees should push round and go through turnstiles to evacuate to safe region. The turnstiles in Basement 2 play a role of taking a great deal of time for evacuation of passengers. The 1-D evacuation model is designed to estimate the Required Safe Egress Time (RSET). This evacuation model treats evacuation path as 1-D unidirectional line, calculates travel speed as a function of density by treatment of the movement of each passenger as motion of individuals, and considers congestion and queuing by using relationship between passenger density and each passenger's travel speed. Once evacuation starts, the movement time can be estimated as:

$$t_{move} = t_{tr} + t_{pas} \tag{1}$$

where t_{tr} is minimum traversal time to an exit [s] and is passage time through an exit [s]. The movement speed can be calculated using the following expression from Nelson and MacLennan [10];

$$S_t = C \cdot (1 - 0.266 \cdot D_O) \tag{2}$$

where D_O is occupant density [persons/m^2] and C is a factor given by 1.4 for level corridors or doorways and $0.86 \cdot (G/R)^{0.5}$ for stairs. G stands for length of the stair trend [m] and R stands for riser height of each step [m].

The minimum traversal time can be obtained as travel distance divided by movement speed.

$$t_{tr} = \frac{L_t}{S_t} \tag{3}$$

where L_t is travel distance [m]. The passage time for passengers to go through a door or stairway can be evaluated by:

$$t_{pas} = \frac{NP}{S_t \cdot D_O \cdot W_e} \tag{4}$$

where NP is the number of passengers passing through door or stairway and W_e is effective width [m]. Effective width is calculated as the door or stairway width minus the boundary layer width. In the present evacuation modeling boundary layer width is 0.15 m for stairway and door.

The evacuation path used in present evacuation modeling consists of subway door, platform, stairway in basement 3, basement 2, subway turnstile, stairway in basement 2, basement 1 and exit to safe region, and is shown in Fig. 4. The numeric values in Fig. 4 represent escape distance from initial location of passenger. The passengers are assumed to be safe when they reach the exit to atmosphere in basement 1. Total evacuation time to safe region can be determined by adding up the traversal time and passage time associated with each evacuation path.

The characteristics of this evacuation model are as follows:

- Movement model: Consideration of crowdedness or congestion and queuing using relationship between density and travel speed. Furthermore, the influence of the stagnation of the passages in any region where width of escape route becomes wider or narrower can be considered in estimating evacuation time.
- Individual model not global model: Treatment of the movement of each passenger as the motion of individuals, namely, ability to calculate the all passenger's RSETs, knowing that all passenger's positions at point in time throughout evacuation.

The factors affected on passenger's movement time such as psychological factor and changes in travel speed due to toxic gas are not considered in this study.

5. Results and discussion

5.1 Prediction of smoke spread

The smoke spread in modeled subway station is investigated by using transient visibility contour because visibility is the most important factor in estimating the time to reach untenable condition. This may cause passengers to panic and interfere with evacuation and lead to disorientation and death of the passengers. The most useful quantity for assessing visibility in a space is the light extinction coefficient which is a product of the density of smoke particulate and a mass specific extinction coefficient that is fuel dependent.

Fig. 5 shows the predicted transient visibility contour at y=2.1 m plane in basement 3 and at y=12.0 m plane in basement 1 and 2 in main evacuation path). As sown in Fig. 5(a) and (b), there is as yet only a little smoke in principal evacuation path in basement 3 although stoppage time is over 100 s because PSD break down at nearly 90 s. The smoke spreads to basement 1 after 300 s and then the time it takes for the smoke to spread to exits is approximately 400 s. During this period basements 3 to 1 in all station are full with smoke. Transient development of the visibility without PSD in principal evacuation path is shown in Fig. 6. As can seen from Fig. 6, the figures reveal the strongly reduced visibility near fire origin and the smoke spreads rapidly in case of platform without PSD rather than in case of platform with PSD by approximately 100 s. That is to say, the smoke spreads to basement 1 after 200 s and then the time it takes for the smoke to spread to exits is approximately 300 s.

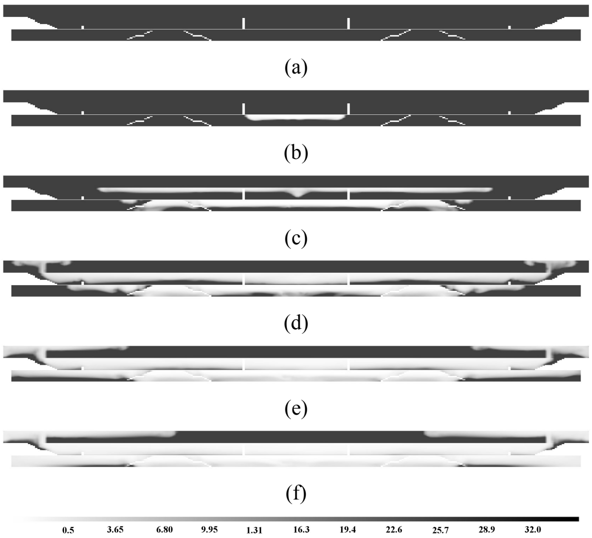

Fig. 5. Visibility Contour with PSD at y=2.1 m plane in basement 3 and at y=12.0 m plane in basement 1 and 2 (a) 50s (b) 100s (c) 200s (d) 300s (e) 400s (f) 500s.

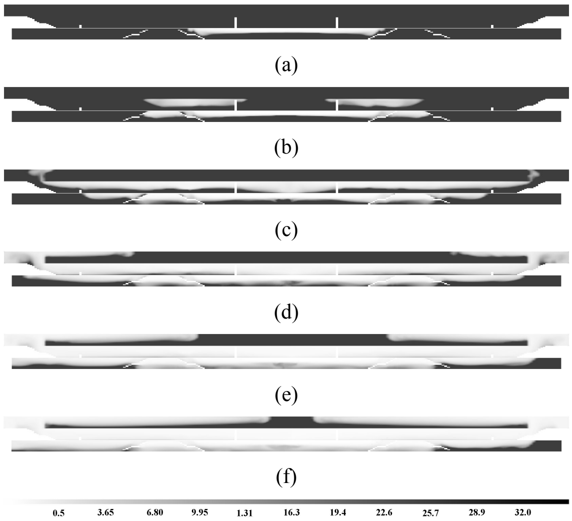

Fig. 6. Visibility Contour without PSD at y=2.1 m plane in basement 3 and at y=12.0 m plane in basement 1 and 2 (a) 50s (b) 100s (c) 200s (d) 300s (e) 400s (f) 500s.

5.2 Prediction of available safe egress time (ASET) and required safe egress time (RSET)

In the present study the time to reach untenable conditions, ASET, is determined by maximum levels of radiation, elevated temperature and visibility. Work by Purser [15] and Scherfig [16] are used in driving what is untenable conditions.

Table 2 shows the limits used for untenable conditions in the present study. The condition first reached determined the time to untenable condition. Thus, ASET is determined as the minimum time to reach the limits in Table 2.

Table 2. Untenable conditions.

Conditions	Level
Radiation	2.5 kW/ m^2
Temperature	80℃ at 1.8 m above the floor
Visibility	10 m at 2.1 m above the floor

FDS calculates radiation, smoke temperature at 1.8 m and visibility at 2.1 m above floor in evacuation path from fire origin to safe region (exits to atmosphere) in basement 1 to obtain the time-dependent ASET.

The number of passengers per carriage is assumed 240 persons, which is estimated from average value of the degree of congestion, which is an indicator of the crowdedness in traffic system, from the No. 1 to 8 subway line in Seoul metro system. The width of subway train door is 1.3 m. Total travel distance to safe region is 139 m and consists of subway door, platform and stairway in basement 3, basement 2, subway turnstile, stairway in basement 2, basement 1 and exit to safe region as can be seen from Fig. 4. Evacuees should push round and go through turnstiles to evacuate to safe region and turnstiles in basement 2 play a role of taking a great deal of time for evacuation. The RSET is obtained from simple travel time relationship from Nelson and MacLennan [10]. There is only travel time in the present evacuation modeling. Thus, RSET is calculated as follows:

$$RSET = \frac{NP}{F \cdot W_e}\bigg|_{\substack{Train\\door}} + \frac{L}{V}\bigg|_{\substack{B3\\platform}} + \frac{NP}{F \cdot W_e}\bigg|_{\substack{B3\\stair}} + \frac{L}{V}\bigg|_{B2} + \frac{NP}{F \cdot W_e}\bigg|_{\substack{turn-\\stile}} + \frac{L}{V}\bigg|_{B2} + \frac{NP}{F \cdot W_e}\bigg|_{\substack{B2\\stair}} + \frac{L}{V}\bigg|_{B1} \quad (5)$$

The results of the ASET and RSET for passengers at prescribed discrete locations in evacuation path are shown in Fig. 7. For both case with PSD and without PSD, untenable condition is mainly determined by radiation for the area around the fire and visibility for the area downstream of the fire.

As can be seen in Fig. 7, the passengers in platform with PSD have much available time of about 80 to 100 s before untenable conditions occur than in platform without PSD. The fact that the slope of ASET with PSD is almost equal to that without PSD shows that the PSD throw back smoke spread before breakdown of PSD in an emergency case of subway fire.

The reason that ASET increase rapidly at a distance of near 50 m and 116 m is that the direction of smoke spread deviates from the direction of evacuees. Therefore, time to reach untenable condition in this local region as shown in Fig. 8 is longer than the other region which corresponds to right region in Fig. 8.

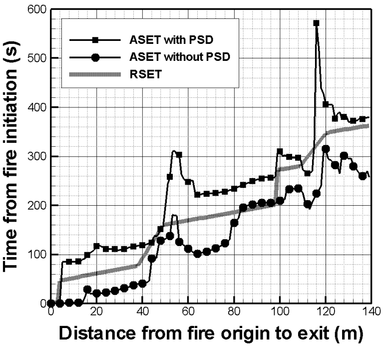

Fig. 7. ASET and RSET analysis.

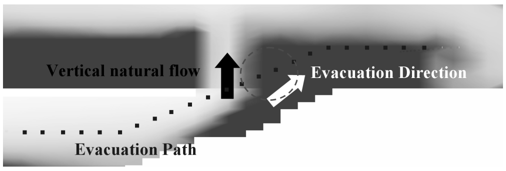

Fig. 8. Smoke spread in connection between stairway and upper stories.

The transient RSET curve shows that time to passage through train door is about 43 s, traversal time to stairway in basement 1 is about 30 s, time to passage through stairway in basement 3 is about 83 s, traversal time to turnstiles in basement 2 is about 41 s, time to passage through turnstiles is about 71s, traversal time to stairway in basement 2 is about 8 s, time to passage through stairway in basement 2 is about 67 s and traversal time to exits in basement 1 is about 15 s. Especially, subway turnstiles (ticket gate) dramatically increase RSET due to jam and bring on danger passengers' life safety. In an emergency case of subway fire, therefore, the passage without barriers like turnstiles will be required not to obstruct evacuation for passengers.

Through the entire evacuation processes it may safely be said that passengers in platform with PSD is safe as the ASET is longer than the RSET. On the contrary, it can be said that passengers in platform without PSD is dangerous as the RSET is longer than the ASET.

6. Conclusions

In this study, fire simulation and evacuation modeling is carried out to estimate the effect of PSD on passenger's life safety in the event of a subway station fire.

The conclusions are as follows.

① The smoke originated in train fire spreads rapidly in platform without PSD rather than that in platform without PSD by approximately 100 s. Therefore, the passengers in platform with PSD have much available time of approximately 100 s before untenable conditions occur than in platform without PSD.

② The subway turnstiles (ticket gate) dramatically increase

RSET due to jam and bring on danger passengers' life safety. Therefore, the passage without barriers like turnstiles will be required not to obstruct evacuation for passengers in an emergency case of subway fire.

③ It may safely be said that passengers in platform with PSD is safe as the ASET is longer than the RSET through the entire evacuation processes. On the contrary, it can be said that passengers in platform without PSD is dangerous as the RSET is longer than the ASET.

Acknowledgment

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Nomenclature

F_C : Calculated flow, persons, person/m s
D_0 : Occupant density, person/m^2
L : Length, m
NP : Number of passenger, persons
K : Kelvin temperature scale
S : Movement speed, m/s
t : Passage time, s
W : Width, m

Subscript

c : Calculated
e : Effective

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