Study on Quantitative Assessment of Road Tunnel Fire Safety

Dissertation

Study on Quantitative Assessment of Road Tunnel Fire Safety

Graduate School of
Natural Science & Technology
Kanazawa University

Division of Innovative Technology and Science

Student ID No. 1223122004
Name: Seike Miho
Chief Advisor: Kawabata Nobuyoshi
Date of Submission: January 2015

INDEX

1. INTRODUCTION

Japan has economic giant in the world, the infrastructure between the Japan islands was developed to sustain the economic activities. However, more than 70 % of the national land is mountains, it was necessary to build many tunnels. Additionally, in the recent year, considerations to influence of environment with activation of the economy demanded, underground urban arterial roads are maintained and tunnel constructions are increasing. Tunnel space is long and enclosed, therefore, evacuation, rescue and extinguish fire activities in fire incidents in tunnels are very difficult and small incidents have a high possibility to cause huge losses. Considered that tunnel fire incident rate rises in Japan, the performance design of tunnel fire safety must be found as soon as possible. The past fire incidents in tunnels indicated to suffer a lot of serious losses, human lives and economic impact. For instance, Nihon-zaka tunnel fire incident in 1979 (7 fatalities, 2 casualties and 173 vehicles burned: Shizuoka, Tomei Expressway) [1], Mont-Branc tunnel fire incident in 1999 (39 fatalities, France and Italy) [2], Gotthard tunnel fire incident in 2001 (11 fatalities, Switzerland) [3]. Measures preventing fire disaster of tunnels in Japan are determined installation of each emergency instruments based on grades (AA, A, B, C and D) which defined tunnel length and traffic volume of year respectively, additionally improved by lessons from Nihon-zaka tunnel fire incidents [4]. Meanwhile in EU, based on the active discussion regarding tunnel prevention disaster measures since Mont-Blanc tunnel fire incident, as a consequent, EU directives were announced officially in 2004, all highway tunnels longer than 500 m length must be investigated safety measurements [5], the strict standard has be applied comparing Japanese.

A number of tunnels in Japanese expressway is as same as the total of the number in EU, it can be said that Japan is a tunnel country of the greatest in the world, more people use tunnel than other countries, hence the higher and more reasonable measures are needed.

Tunnel fire dangerous factors are regarded as depending on traffic volume and tunnel length, however, it is considered that topographical conditions as cross section, longitudinal gradient, and geometrical conditions as natural ventilation velocity have huge influence when fires in tunnels occur. However, influence of these factors has not been evaluated on system in the range that authors searched. The present study has been started to clarify the influence of the factors, however, at first, the quantitative assessment regarding safety or danger of tunnel fire incidents is needed. In the primary present research, the method of the quantitative assessment with regard to tunnel fire safety is reported. If tunnel fire safety can be assessed quantitatively, quantitating effect of tunnel emergency equipment, the performance design which is the most effective and low cost, can be clarified, and it is believed that the present study will be contributed to solve the tunnel fire safety. In references [6], [7], [8], number of fire accidents in tunnel Evacuees behavior map in each cases of emergency announcement time in Fig. 1. It can be seen that the number of fire accidents in tunnel become increasing tendency in Fig. 1.

The assessment method suggested in the present research is that evacuation simulation has been simulated based on smoke's behavior by 3-D CFD Analysis, and the tunnel fire safety has been assessed by calculated a number of occupants who were surrounded with thick smoke in a fixed time. Two characteristics of the evacuation simulation in this study has been indicated, first one is defined Smoke Environment Levels (SE levels, see chapter 3) and second one is one-dimensional evacuation simulation. SE Levels are indicated around ten grades of simple smoke's situation on each locations with the elapsed time respectively and evacuees' walking velocities, etc. are defined based on the SE levels. Additionally, an isocline map, which is defined SE map, is developed by the SE levels with the horizontal axis and elapsed time with vertical axis. The SE map can be indicated smoke's behavior with elapsed time only one figure. With regard to the evacuation simulation (see chapter 4), considering tunnel space where is long and enclosed, thermal fume flows stratified and propagate uniformly in transverse section, human behavior is ruled by smoke density and evacuating direction is almost limited one-direction due to tunnel length being much longer than tunnel width. Additionally, putting in the exchange information between evacuees in the simulation is also the characteristic in the present research.

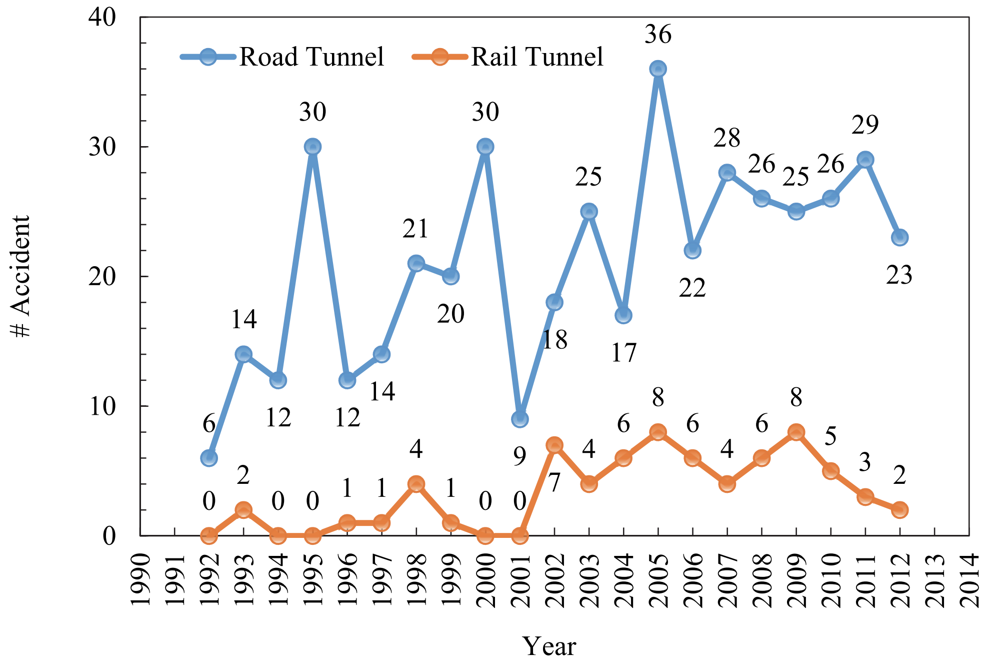


Fig. 1 Number of fire accidents in tunnel [6], [7], [8]

NOMENCLATURE

Wide averaged optical smoke density : optical smoke density by wide averaged, so that the number is function of *x*, *z*, and time *t*.

SE level : The simplified amount of the influence degree to evacuees by smoke (see Table 1).

SE map : the counter diagram of SE levels by tunnel length as the horizontal axis and elapsed time as the vertical axis.

Evacuees behavior map : the diagram described all evacuees' loci on the SE map.

Impossible to move : the situation that evacuees cannot evacuate accurately due to smoke.

People requiring help : people needed to rescue because of it impossible to move.

x, *y*, *z* : Cartesian coordinate system is used, where *x*, *y*, and *z* are along the tunnel longitudinal direction, the span wise direction and the vertical direction, respectively. The fire source is taken as the origin of the coordinate system.

t : Elapsed time after ignition [min]

g : Longitudinal gradient of tunnel [%]

L : Longitudinal length of tunnel [m]

Cs : Optical smoke density [m^{-1}]

$$Cs = -\frac{1}{(\text{Distance traveled by light})}\ln\frac{(\text{Intensity of incident light})}{(\text{Intensity of transmitted light})}$$

2. SMOKE'S BEHAVIOR SIMULATION

2.1 3-D LES CFD Simulation

In the present study, LES turbulence model (standard Smagorinsky model) 3-D CFD analysis (Fireles) is used. Fireles was developed in 1998 in Japan by one of authors, specialized tunnel fire, endothermic model to the ceiling and wall, which influenced dominantly to the thermal layers' behavior, considered since initial stage developing the simulation. Flow phenomena of smoke descending and propagation in tunnel fires were investigated by comparison Fireles with experiments in full-scale and scale tunnels, and Fireles can reproduce thermal layers in tunnel fires quantitatively. Especially the location and time of smoke descending were agreed well the results between the experiments of real scale tunnel fires and the present simulation [9], [10], [11], [12], [13]. In the prevention of fire disasters in Japanese road tunnels, 3-D CFD analysis (Fireles) [9], [10], [11], [12], [13], is general method.

FDS (Fire Dynamics Simulator) is used as general tool by other countries [14]. FDS is open source fire simulator, which was developed as the target for building fire by NIST (National Institute of Standards and Technology, USA) in 2000 [15]. FDS was developed with subject to building fire, therefore, FDS's characteristics are to treat near the fire source as thermal flow in the vicinity of the fire source or influence of radiation heat. Incidentally, tunnel fires were simulated by FDS in these days, however, there exists few evaluation with experiments, smoke's behavior in tunnel fires, especially smoke descending phenomenon, which is important characteristic in tunnel fires, has not been investigated by comparing with experiments.

2.2 Smoke Density

Factors preventing the evacuees in tunnel from evacuation in fires are considered temperature rising, toxic gas (generally CO) and smoke density around evacuees. Especially temperature and smoke are considered as the same behavior in building fires, so that temperature is used [16].

Meanwhile, tunnel internal volume is large, and the length is more than hundreds meter long, so that tunnel space is so that tunnel space is considerable to use smoke density appropriately. Additionally tunnel fire scale is supposed as large shortly, therefore, heat absorption by the ceiling and walls are governed the thermal plume and behavior of smoke because thermal plume flows with much smoke in the large range, so that thermal and smoke layers are different behavior far from the fire source. As a consequence, it is used CO or smoke density as barometers of evacuation in tunnel fires generally [17], [18]. CO density is used as the barometer in EU because many victims caused CO poisoning to die [14]. In Japan, smoke density is used as assess the evacuation environment because evacuees' visibility goes bad by smoke and then evacuees can't evacuate anymore before evacuees dying, worsening of the visibility by smoke is governed the evacuation. In the present study, Concentration of smoke (*Cs*), which is a kind of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density.

It is not appropriate to calculate using convective diffusion equations directly which are used in CFD. In the present study, smoke mass concentration having preservative quality from convective diffusion equations were calculated, and transformed smoke mass concentration into smoke density, referring experiment results [18].

$$\left.\begin{array}{ll} Cs = 10m & m \leq 0.26[\mathrm{g/m^3}] \\ Cs = 1.73 \ln m + 4.94 & m > 0.26[\mathrm{g/m^3}] \end{array}\right\} \qquad (1)$$

where, m: smoke mass concentration.

2.3 Boundary conditions

Boundary conditions in CFD analysis example are all the same in the present study. This section accounts for the boundary condition.

2.3.1 CFD Analysis condition

Model tunnel was adopted a rectangular section, the total length of 700 meters, 5 meters height, 10 meters width, two-lane and one-way, which were not installed ventilation instrument and emergency announcement (see Fig. 2). Longitudinal gradient in the tunnel g rose with x positive direction constantly, no ventilation velocity was happened before fire occurred. The computational grid sizes in the model tunnel were equal divisions, 0.40 m in the x direction, 0.30 m in the y direction, 0.25 m in the z direction, and the total of the grid number was around 1170 thousand referring to the reference [12].

Fig. 1 shows a schematic diagram of an analytical tunnel of the simulation, also included exterior domains. This is because the flow occurs by the buoyancy of thermal layers from down to upper portals in tunnel with gradient, the influence of the inflow residence cannot be neglected. Additionally, the initial velocity was decided 0 m/s, so that the influence was considered not large, for calculation efficiency, L_x = 16 m, L_y = 15 m and L_z = 9 m, 2160 m^3 of the volume were determined. The division in the exterior domains were unequal, to improve the number of calculation cells efficiency, the total of the number of cells which included the tunnel was around 1300 thousand. In the case of existing the differences between both portals, natural ventilation velocity has around 2 % differences comparing with enough exterior domains.

The ceiling and wall in tunnel was used concrete, which was density 2100 kg/m^3, specific heat 879 J/(kg·K), thermal conductivity 1.10 W/(m·K), and thickness 500 mm. Inside of the wall also was 9 divisions to the thickness direction and thermal conductive function was analyzed by 2-way coupling.

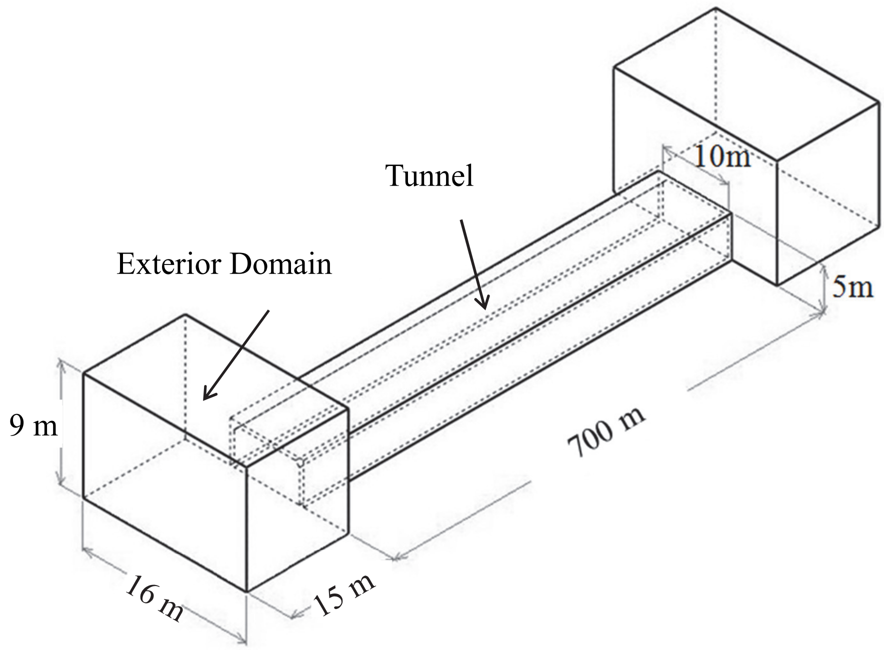


Fig. 2 Calculation Domain

2.3.2 Fire scenario

In Japan fire scale of a large bus fire is mostly used to investigate fires. Fig. 3 expressed the convective heat release rate and smoke particles generation rate curve in the present study and pictures of the full-scale model tunnel fire experiment (g = 2 % and u_0 = around -2 m/s)[12]. Maximum of convective heat release rate of 20 MW [12] and max smoke particles generation rate of 90 g/s [18] were obtained at 8 minutes from fire ignition. Convective heat release rate was between 60 % and 2/3 the total of heat release rate, hence fire scale was a large vehicle of 30 MW in this study. Convective heat release rate curve was the result from No.3 Shimizu tunnel bus fire [12], which has been reported almost same as convective heat release rate of EUREKA school bus fire experiment result [12], [19].

Fire accident occurred in 200 meters (x = 0 m) from left exit. Traffic jam occurred to the right portal (x = 500 m) from the fire source (x = 0 m). The positive direction from left to right portals was defined. x was the distance from the fire point to right direction (the origin was x = 0 m). Hence the fire source was supposed as the dangerous side.

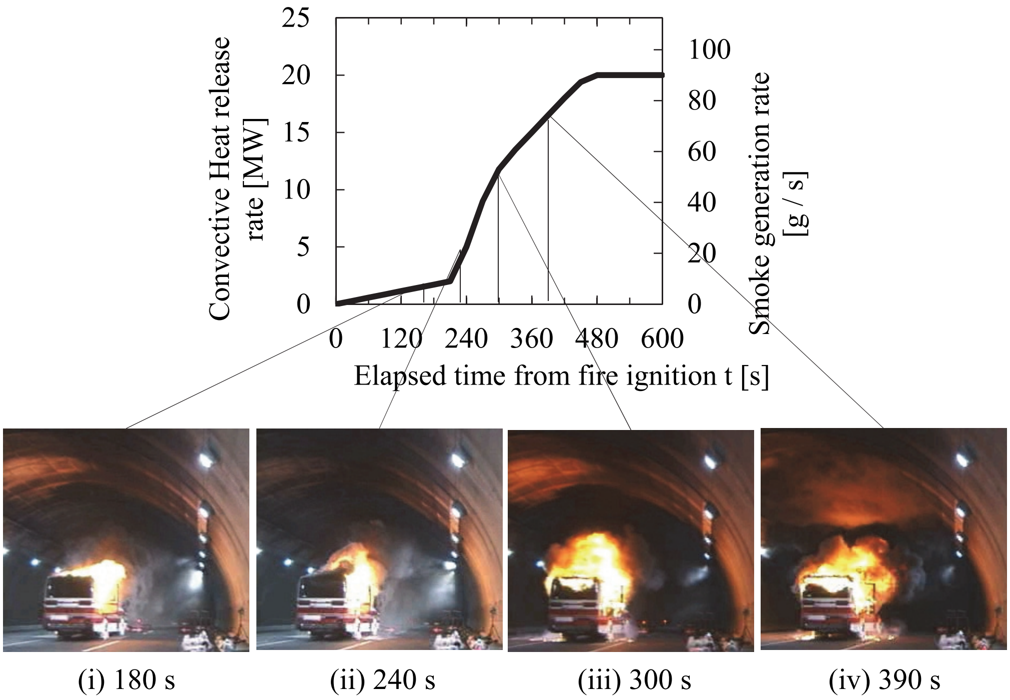


Fig. 3 Heat release rate and smoke generation rate curves corresponding with the actual pictures of a large bus fire in the full scale tunnel [12]

2.4 Summary

In the present chapter, considered characteristics of tunnel fires calculation code, assessment index, geometries and condition are determined. Main results are as follows;

1. Considering thermal flow in tunnel fires, in the present study, LES turbulence model (standard Smagorinsky model) 3-D CFD analysis (Fireles) is used. Fireles was developed in 1998 in Japan by one of authors, specialized tunnel fire, endothermic model to the ceiling and wall, which influenced dominantly to the thermal layers' behavior, considered since initial stage developing the simulation.
2. Factors preventing the evacuees in tunnel from evacuation in fires are considered temperature rising, toxic gas (generally CO) and smoke density around evacuees. However, tunnel internal volume is large, and the length is more than hundreds meter long, so that tunnel space is considerable to use smoke density appropriately. Also in Japan, smoke density is used as assess the evacuation environment because evacuees' visibility goes bad by smoke and then evacuees can’t evacuate anymore before evacuees dying, worsening of the visibility by smoke is governed the evacuation. In the present study, Concentration of smoke (*Cs*), which is a kind of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density.
3. Model tunnel was adopted a rectangular section, the total length of 700 meters, 5 meters height, 10 meters width, two-lane and one-way, which were not installed ventilation instrument and emergency announcement.
4. Fire scenario is determined by the past experiment [12] and Japanese standard.

3. SE LEVEL

3.1 Definition of SE Level

Smoke distribution in tunnel fires can be expressed two-dimensional distribution of the longitudinal x and vertical z sections because the declension of the transvers section is few. Therefore, to show simplifying the smoke situation around evacuees, smoke environment levels (SE levels) are determined from z directional distribution of Cs_y (x, z), which can be obtained 2-D distribution averaging 3-D Cs density distribution by CFD analysis, as influence degrees which smoke hinder the evacuees' activities, at any x point on time t. That is SE levels become function of x and t.

Table 1 shows definition of SE levels in the present paper. Before the fire ignition, there exists no smoke, SE level become 0 at any x point. Thermal plume and smoke occurs form the fire source, smoke spreads with thermal plume along the ceiling and smoke density rises near the ceiling. It is considered whether lights near the ceiling surrounded by smoke in the present study, the rectangular cross-section of the tunnel was investigated, which height H was 5 m, therefore, Cs density at z = 4 m around the height of the lights was noted, the value becoming larger than 0.4 m^{-1} was defined SE level 1. Additionally, in the more dangerous situation, SE level 1 was defined as smoke spreading, the situation that Cs density at z = 1.5 m becomes less than 0.1 m^{-1}. Hence, the situation between Cs = 0.4 m^{-1} at z = 4 m and Cs = 0.1 m^{-1} at z = 1.5 m was defined as SE level 1. Cs = 0.4 m^{-1} is the situation which the volume of the light reduces around 50 % between 1.7 m distance, and Cs = 0.1 m^{-1} is the situation which the volume of the light reduces around 50 % between 7 m distance. Furthermore smoke diffusing, the situation between Cs = 0.1 m^{-1} at z = 1.5 m and Cs = 0.2 m^{-1} at z = 1.5 m was defined as SE level 2, and the situation between Cs = 0.2 m^{-1} at z = 1.5 m and Cs = 0.4 m^{-1} at z = 1.5 m was defined as SE level 3. Cs = 0.2 m^{-1} is the situation which the volume of the light reduces around 50 % between 3.5 m distance, it is considered that occupants can evacuate although the field of vision limited [17]. Next, the situation between Cs = 0.4 m^{-1} at z = 1.5 m and Cs = 0.4 m^{-1} at z = 1 m was defined as SE level 4. It is considered that Cs = 0.4 m^{-1} at z = 1.5 m is used very often as the critical value that is possible to evacuate in Japanese road tunnel prevention of disaster [1], [17]. Additionally, noted dangerous situation as the eye's height where evacuees bend down, the situations between Cs = 0.4 m^{-1} at z = 1 m and Cs = 0.8 m^{-1} at z

= 1 m, between Cs = 0.8 m^{-1} at z = 1 m and Cs = 1.2 m^{-1} at z = 1 m and more than were defined as SE level 5 and 6 respectively.

Table 1 SE Level

SE Level	Smoke Density Cs [m^{-1}]	Smoke Height z [m]
0		
	0.4	4.0
1		
	0.1	1.5
2		
	0.2	1.5
3		
	0.4	1.5
4		
	0.4	1.0
5		
	0.8	1.0
6		
	1.2	1.0
7		

3.2 SE Map and smoke behavior

Smoke Environment map (SE map) was developed contour diagram based on SE levels (colors of Table 1) and letting elapsed time from the ignition be the vertical axis and the tunnel length the horizontal axis. Fig. 4 is expressed SE map in the case of g = 2 % and u_0 = 0 m/s. To show that SE map can be seen the behavior of smoke with time, every 1 minute smoke distribution of longitudinal (x-z) section of the tunnel averaging transvers section Cs_y is expressed in Fig. 5. Note that colors in Figs. 4 and 5 show SE levels and smoke optical density respectively. Comparison with SE map in Fig. 4 and smoke optical density in Fig. 5, SE maps can be shown the smoke behavior with time elapsed as below. From 20 seconds to 2 minutes after fire started, as can be seen in Fig. 5, smoke spread along the ceiling, in the same time, Fig. 4 shows SE level 1's blue spread but not descended to the floor where evacuees existed. Border line between SE level 0 (white) and 1 (blue) is indicated the tip location of smoke spreading, the inclination of the border line is the velocity of smoke. After 2 minutes from the ignition, the smoke advance velocity on the left portal side was slower, and the velocity on the right portal side was more rapid. This is because thermal layer's region of high temperature spread along the ceiling, the buoyancy became also large, and started to move to the upper side. In 3 minutes from fire ignition, smoke was shown SE level 2 (sky blue) 3 (orange) and 4 (yellowish green) described in x = 100 m in Fig. 4, which are defined the situation where smoke descended to z = 1.5 m, and stripe lines of SE levels 2 to 4 was expressed from x = 100 m to negative direction of x in Fig. 4. That is, the smoke layer at x = 100 m was thicker and descended to near the floor, flowed to fire source near the floor in Fig. 5. As can be seen in Fig. 4, 4 minutes later from ignition, beyond x = 100 m SE level 4 region moved to positive side a little later, backlayered to the fire source in negative side, and spread rapidly to the both of left and right directions. It was confirmed that smoke layer of right side was thicker and descended to the floor in a large range in Fig. 5. In 5 minutes from the ignition, SE level 5 (pink) and 6 (yellow) was expressed between x = 100 m and 200 m in Fig. 4, which are defined the situation where smoke descended to z = 1 m, SE level 7 (red) was shown immediately, thick smoke larger than Cs density 1 m^{-1} descended to the floor since 5 minutes, it could be read that thick smoke descended in a large range. Additionally, in a tip point of smoke, smoke did not stratify and smoke spread in the whole transverse section, because Fig. 4 expressed from SE level 0 to 7 immediately.

Meanwhile, till 6 minutes from the ignition, in the side of the lower gradient from the fire source (left side) smoke layers was constant stratified and went to the left portal, but in 7 minutes smoke layers thicker near the fire source and reduced thickness to the left portal, because the positive longitudinal (x) velocity increased with buoyancy, thermal layer started to back with the flow. As can be seen in Fig. 4, the left side of the fire source was SE levels 0 or 1till 6 minutes, which smoke stratified, but between 6 and 7 minutes SE levels 2, 3 and 4 appeared from x = - 80 m to the fire source, additionally, since thermal layer arrived the left portal in 7 minutes, SE levels 2, 3 and 4 appeared near the left portal and flowed to the fire source. It was considered that thermal layer was perturbed by air flow from outside going into the tunnel. Thermal layer of the right side accelerated since 6 minutes, arrived to the right portal less than 8 minutes. Smoke in the left portal did not descend 8 minutes past, and thermal layers backed to the fire source. The longitudinal velocity from the left side of the fire source to the right portal increased by buoyancy and pushed back thermal layer, since 9 minutes the environment of the left side from the fire source recovered immediately. Therefore, behavior of thermal layer can be read from SE map.

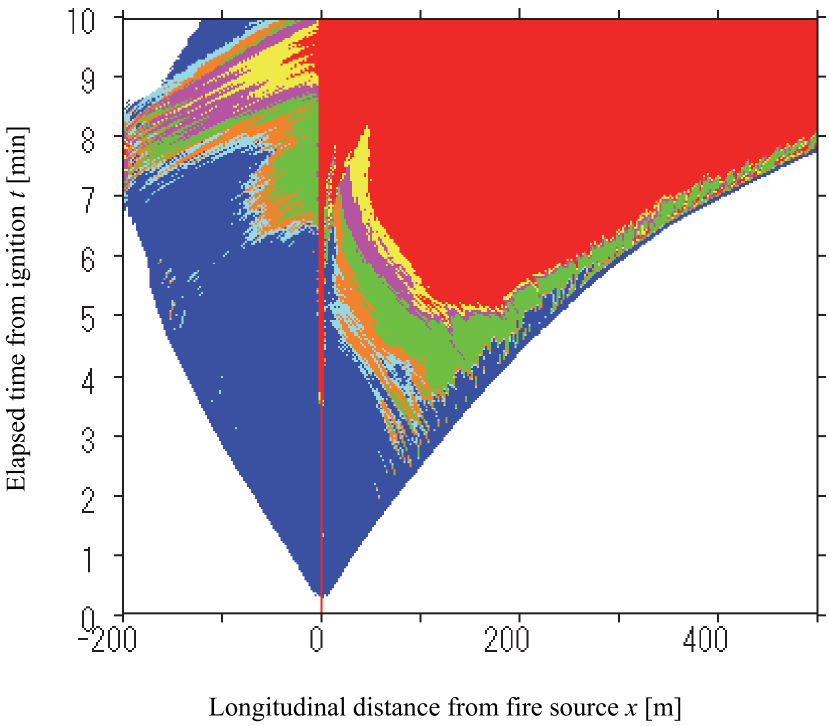


Fig. 4 SE map (g = 2 %)

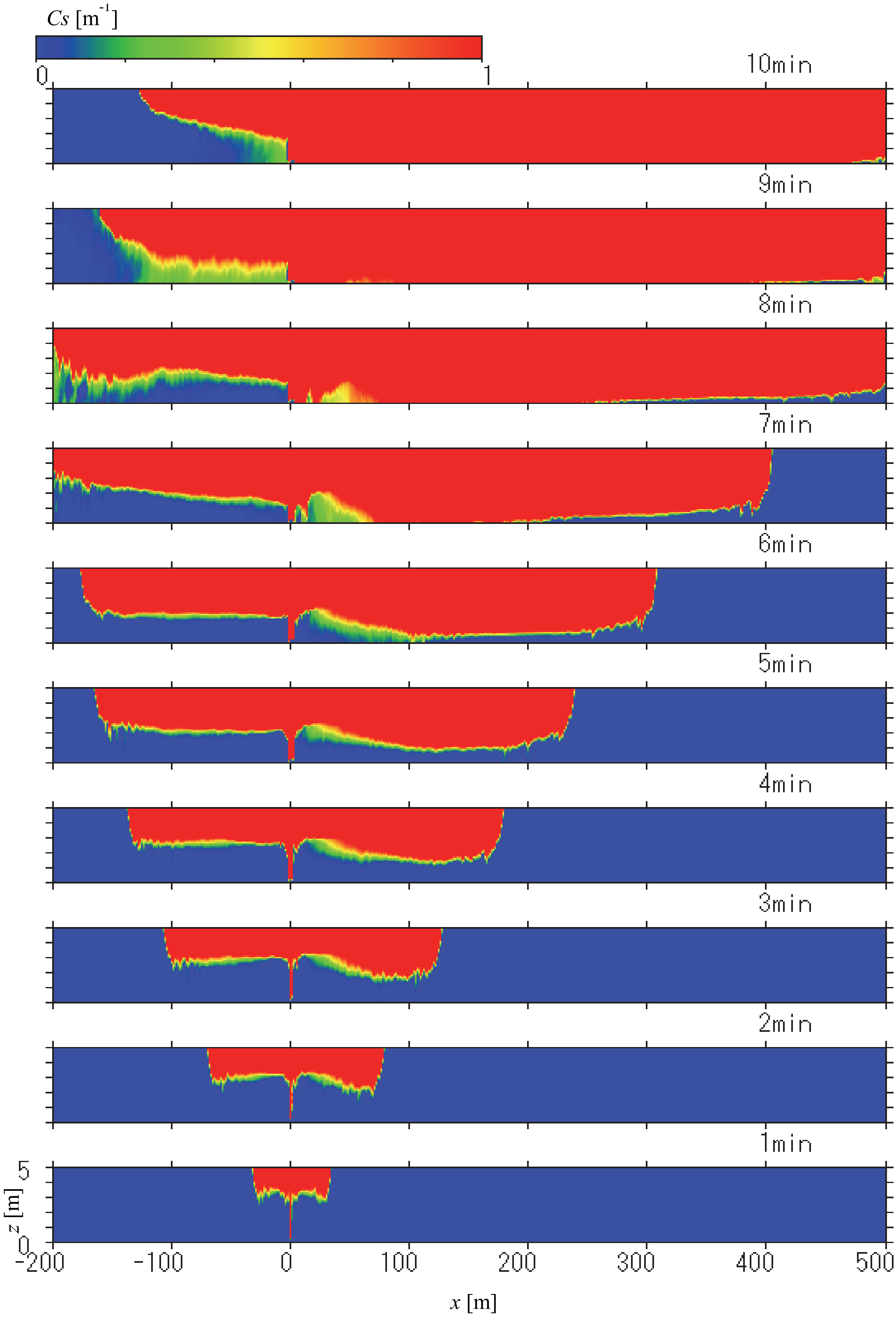


Fig. 5 Longitudinal smoke distribution every 1 minute (g = 2 %)

Fig. 6 shows SE maps as same of Fig. 4 to compare smoke behavior in the case of g = 0 %. Additionally, Fig. 7 shows longitudinal smoke distribution. In the case of g = 0 % of Fig. 6, in 5 minutes from the ignition, SE level 1 (blue) spread the left and right sides and kept stratified. Since 5 minutes, SE level 4 (yellowish green) spread between $x = \pm$ 100 m immediately and started to descend. Smoke descending at the right side from the fire source spread to the right portal and caught up the tip of smoke (the border line between SE levels 0 and 1) around 6 and half minutes. In 7 minutes, SE level 6 moreover 6 appeared in large range between x = - 100 m and 150 m, and kept descending. In 9 minutes, thick smoke descended to the floor at x = 300 m. Comparing the case of g = 2 % in Fig. 4, it was indicated that the time when smoke was stratified was long and evacuating environment in the right side of the fire source was better than that of g = 2 %.

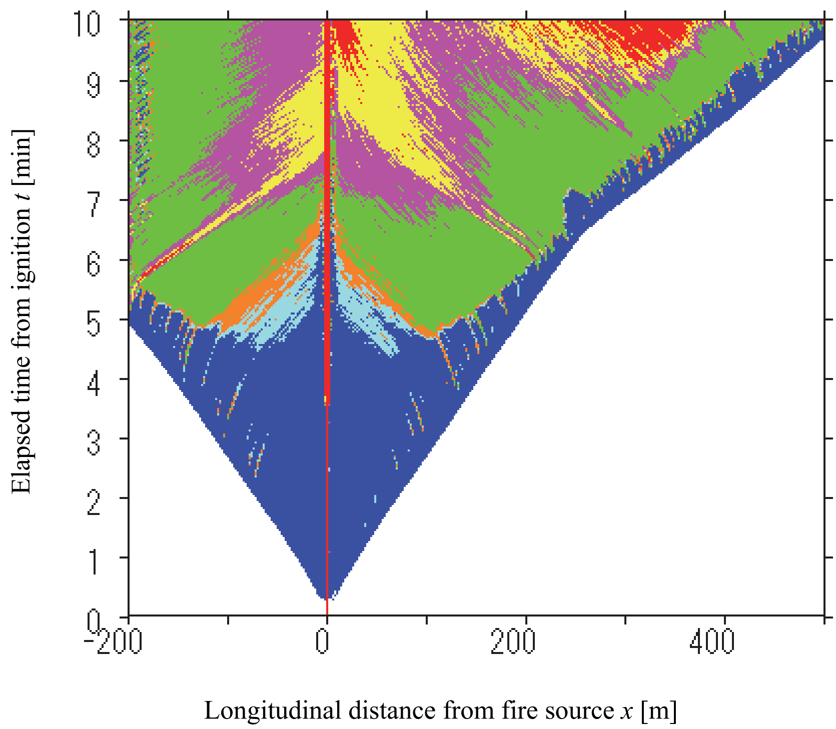


Fig. 6 SE map (g = 0 %)

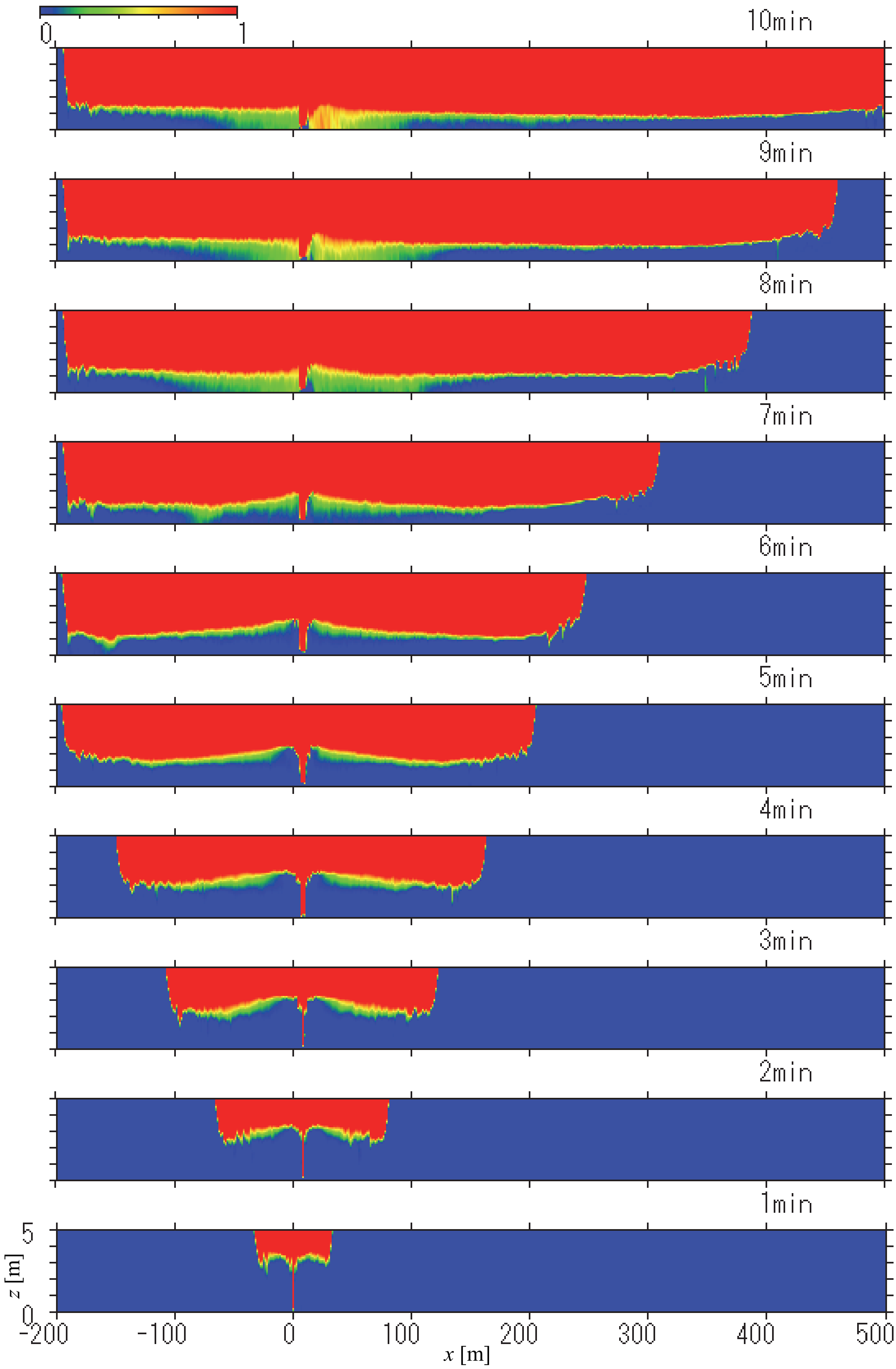


Fig. 7 Longitudinal smoke distribution every 1 minute (g = 0 %)

Fig. 8 shows SE maps as same of Fig. 4 to compare smoke behavior in the case of g = 4 %. Additionally, Fig. 9 shows longitudinal smoke distribution. In the case of g = 4 % of Fig. 8, SE level 1 (blue) spread the left and right sides and kept stratified in 2 minutes from the ignition as almost the same of the cases of g = 0 % and 2 %, but buoyancy to the right side occurred, which caused by the longitudinal gradient, the tip of smoke velocity reduced and stopped at x = - 100 m in 4 minutes. 6 minutes past from the ignition, smoke started to back to the fire source and since 8 minutes smoke did not exist in the left side of the fire source. Additionally, it can be read from the figure that more than SE level 2 did not appear in the left side of the fire source, hence, smoke kept stratified. The range of SE level 1 (blue) was small in the point of smoke in the right side from the fire source, smoke descending in the whole transverse section went to the right portal, that is smoke did not keep stratified, arrived the right portal in 7 minutes, when the time was faster 1 minute than the case of g = 2 %, hence it is indicated that the evacuating environment was more seriously dangerous than that of g = 4 %.

Therefore, as can be shown thermal layer behavior from SE maps. For reference, SE maps in cases of (i) g = 0.5 %, (ii) 1 %, (iii) 1.5 %, (iv) 2.5 % and (v) 3 % indicate in Fig. 10.

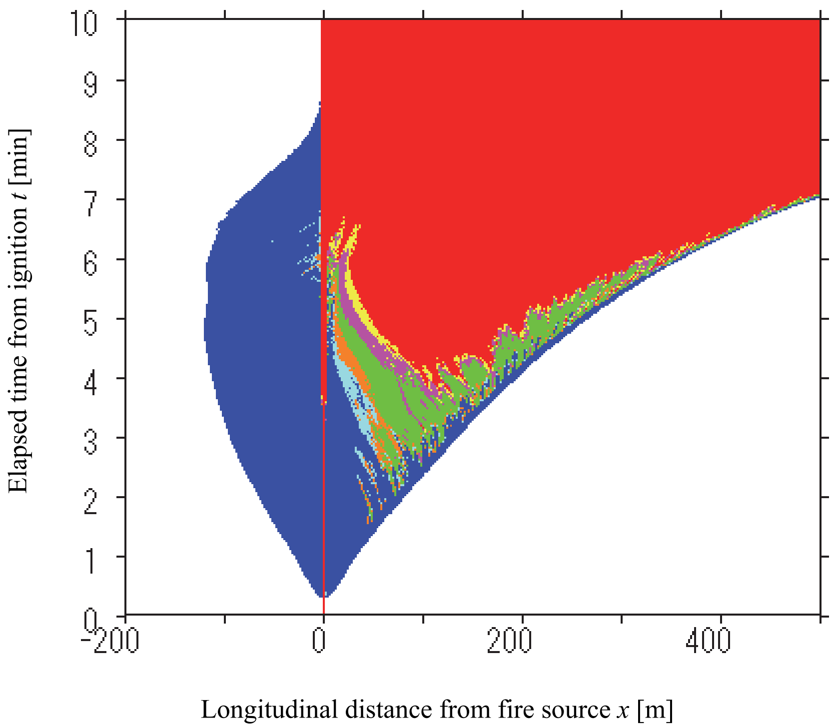


Fig. 8 SE map (g = 4 %)

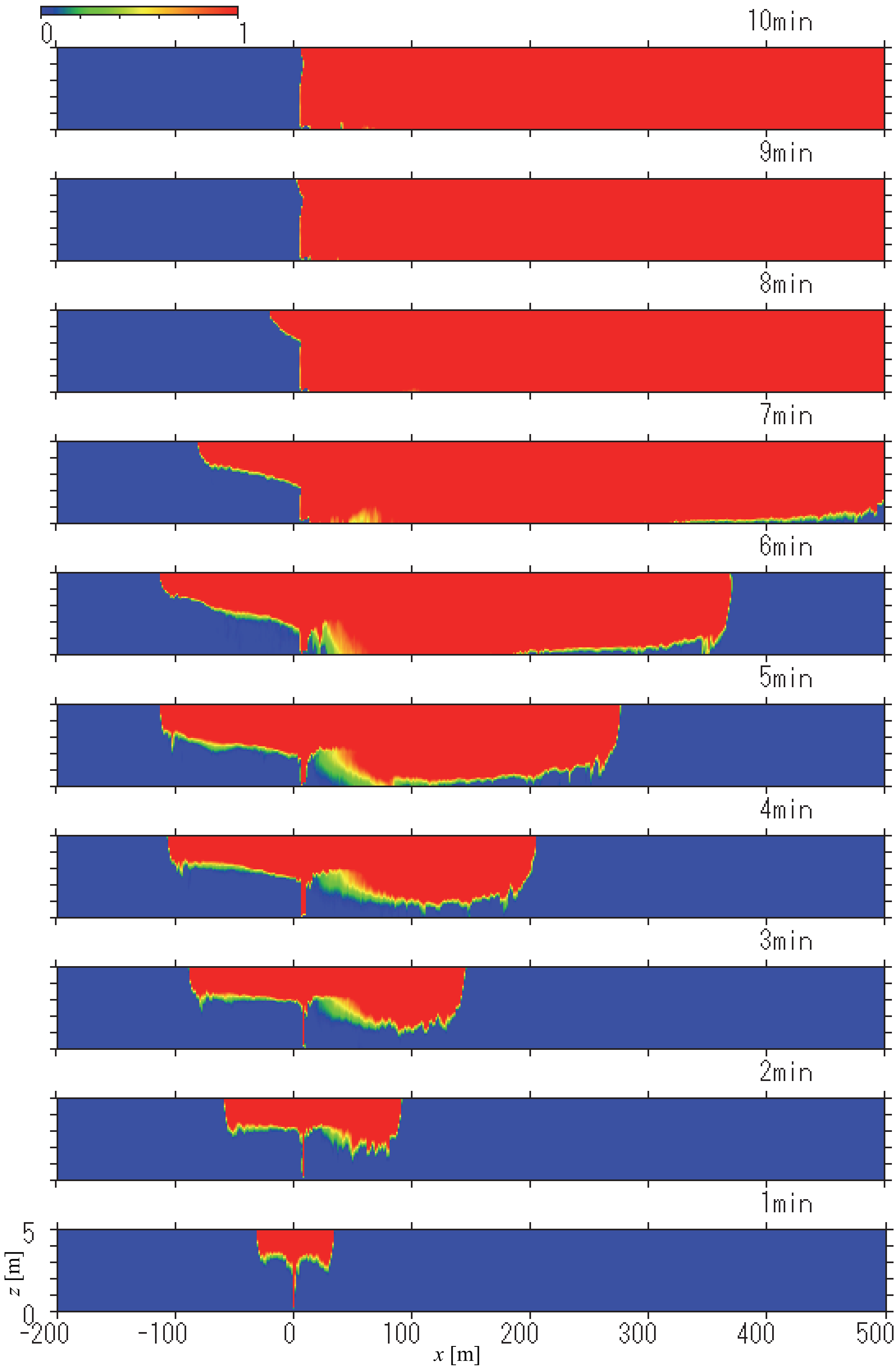
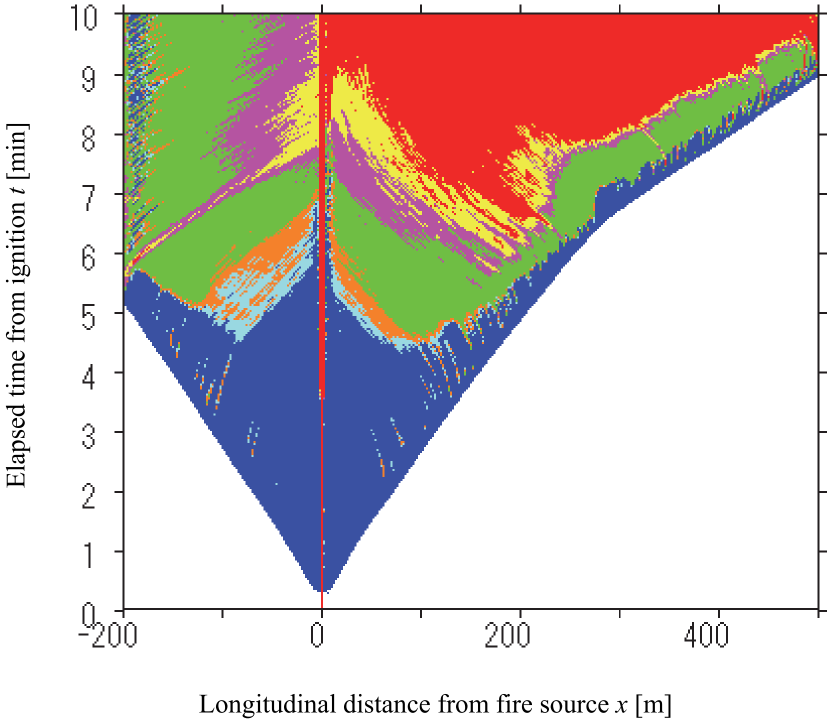
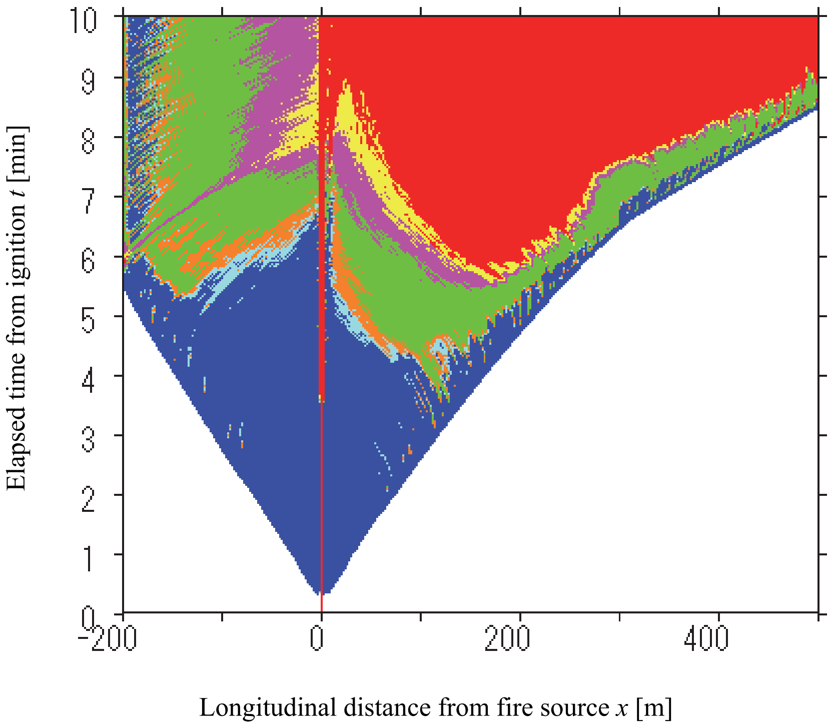


Fig. 9 Longitudinal smoke distribution every 1 minute (g = 4 %)



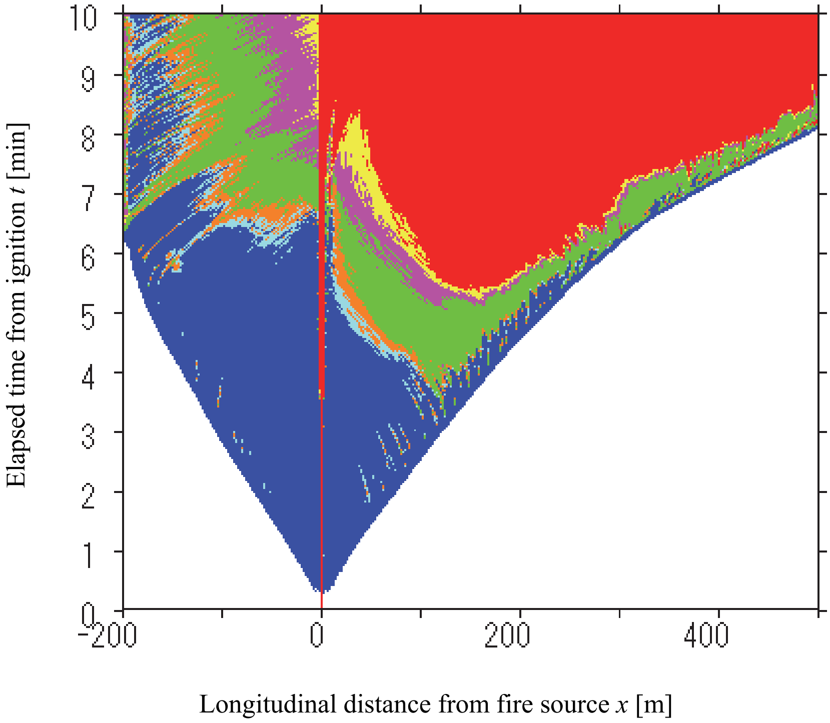
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Elapsed time from ignition *t* [min]
Longitudinal distance from fire source *x* [m]

(i) $g = 0.5$ %

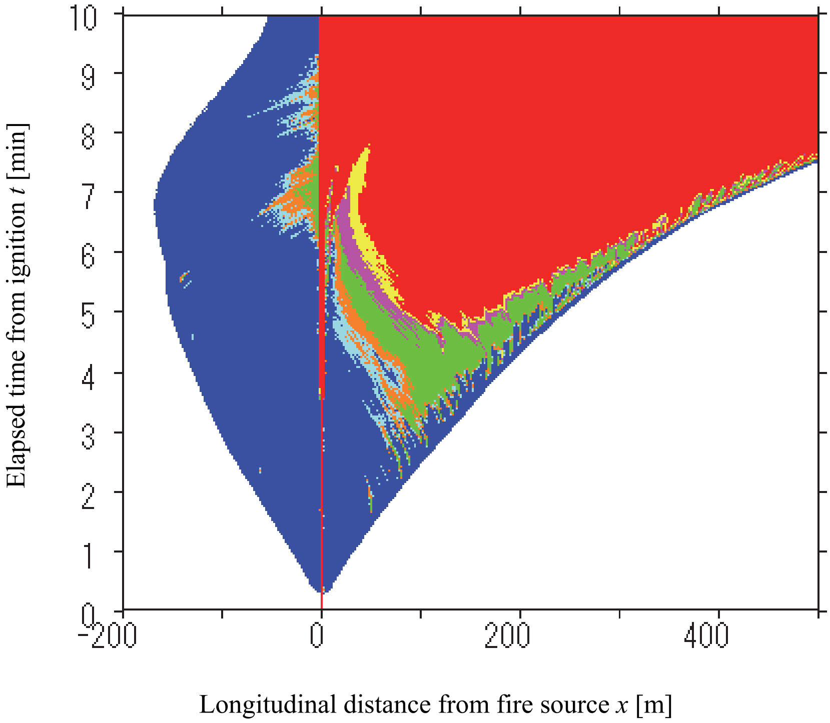


10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Elapsed time from ignition *t* [min]
Longitudinal distance from fire source *x* [m]

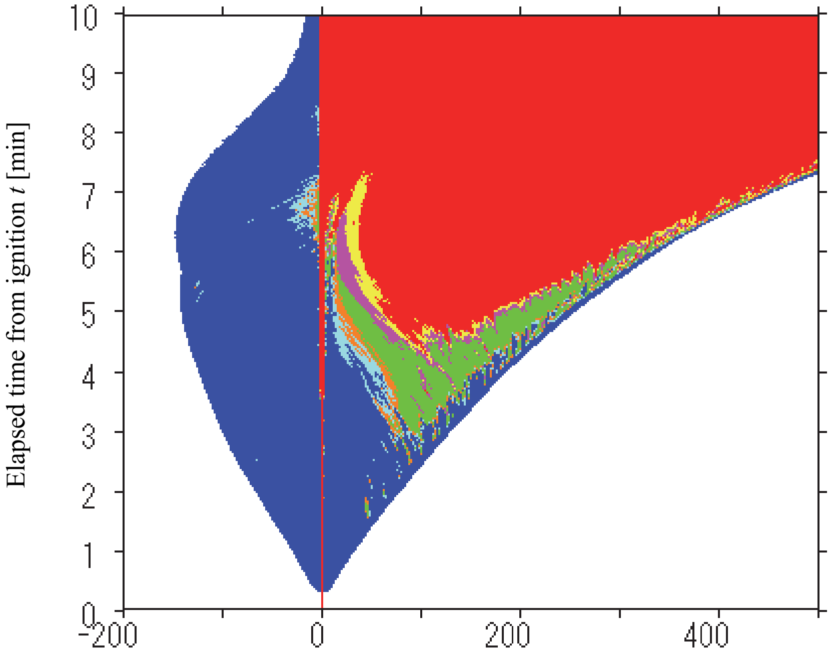
(ii) $g = 1$ %



(iii) g = 1.5 %



(iv) g = 2.5 %



(v) g = 3 %

Fig. 10 SE map

3.3 Summary

In the present chapter, simplifying the smoke situation around evacuees, smoke environment levels (SE levels) are determined from z directional distribution of Cs_y (x, z), which can be obtained 2-D distribution averaging 3-D Cs density distribution by CFD analysis, as influence degrees which smoke hinder the evacuees' activities, at any x point on time t. Main results are as follows;

1. Considering tunnel height and evacuees situation, SE levels determined as an index of influence for evacuees by smoke height and Cs density.
2. Smoke Environment map (SE map) was developed contour diagram based on SE levels (colors of Table 1) and letting elapsed time from the ignition be the vertical axis and the tunnel length the horizontal axis. Thereby, behavior of thermal layer can be read from SE map.

4. EVACUATION BEHAVIOR SIMULATION

Regarding evacuation behavior models, there exist almost past studies treated evacuation inside buildings and huge disasters. References, which predicted model of a group with homogeneous property which is treated as the number of evacuees, are suggested [20], recent year, other evacuation models considering each of evacuees are suggested, for instance distinct element method used equation of motion which a phenomenon activates to each of evacuees [21], [22], [23] and potential-based evacuation model [24], [25], [26] given the locations where is dangerous or direction to evacuate in evacuees existing.

Research for evacuation behavior simulation in tunnel fires are few in Japan, there only exist the paper by Ohkami etc. [27]. Ohkami's evacuation behavior model is horizontal two dimension considered obstacles like vehicles which stops due to traffic jam, meanwhile regarding smoke behavior, stratified and diffused smoke are not considered, that is, extremely simple model, a constant smoke velocity without analysis of smoke behavior is adopted.

In the past studies about the evacuation in fire, potential-based evacuation model [28], buildingEXODUS [29], cellular automata model [30] have been developed on the subject of buildings, and control volume model on the mass rapid transit station [31]. These put importance human behavior, but not smoke environment.

However, smoke behavior inside tunnels makes a great impact on evacuees' behavior, smoke behavior consists complicated behavior in tunnels with gradient, natural ventilation, application of ventilation facilities, heat release rate scale, etc., moreover, evacuation under the smoke layer has to be supposed, hence evacuation behavior simulation using smoke behavior detailed analysis is necessary. In the present paper, using SE levels in chapter 3 by 3-D LES-CFD analysis in chapter 2, the evacuation behavior simulation considered smoke optical density is suggested. Evacuees' behavior does not influence to smoke behavior, so that evacuation behavior simulation in the present paper becomes 1-way coupling to CFD analysis of smoke behavior.

4.1 One dimensional model of evacuation behavior

The present suggested evacuation behavior model is chasing each evacuees' behavior, and considering each evacuees' phenomenon occurred in evacuating. Tunnel spaces are extremely long comparing with wide length, but having around 10 m wide, so that tunnels are huge, enclosed and unique. Meanwhile, tunnel users existing concentratedly in a place are seldom, but are dotted with traffic jam sections. Therefore, when evacuees go through roadways where become evacuation passages in emergency situation, even if there are vehicles stopped, it can be considered that evacuees can go through the side easily, influence of physical interference between evacuees is disregard, so that it is defined that evacuees can pass the others. Also evacuees can recognize the longitudinal direction of tunnel and to lose sight of the evacuation direction is not considered, so that evacuation behavior is treated one-dimensional behavior limited to longitudinal x direction.

An evacuee's location x_i and a walking speed v_i, where the suffix i indicates a location can be obtained with the location change ($x_i^{old} \rightarrow x_i^{new}$) at infinitesimal time Δt as following relation.

$$x_i^{new} = x_i^{old} + v_i \Delta t \tag{2}$$

The walking speed v_i is determined based on various situations, and time is elapsed. Therefore, before starting evacuation v_i becomes 0, v_i is determined by the situation of smoke around the evacuee, so that SE levels after the evacuation, and finishing evacuation v_i becomes 0.

4.2 Evacuation necessity recognizing model

In building fires, multiple compartments are divided inside buildings, and high-rise, almost occupants cannot recognize fires directly, so that recognizing fire must rely on the fire detector and emergency announcement. In this background, a movement time of evacuation is determined by a fire room area, and necessary time of evacuation is calculated [32]. Meanwhile, tunnel space is long and large, and there exist almost evacuees inside a same space where fire occurs, so that the situation that evacuees recognize the necessity of evacuation in tunnel fires is different from building fires. Hence the factors to recognize the necessity of evacuation are determined phenomena around evacuees, communication by other evacuees and information by the outside.

(i) Phenomena around evacuees (smoke along the ceiling)

The ceiling in tunnels is dirty, additionally almost users stay inside the vehicles, so that it is difficult to find the smoke along the ceiling. Therefore, the lights along the ceiling covered with smoke make dark, and then users find the unusual factor, recognize the necessity of evacuation and start to evacuate is considered. In the present paper, when the upper side of users becomes SE level 1 (see Table 1), evacuees recognize the necessity of evacuation (see Fig. 11 (i)).

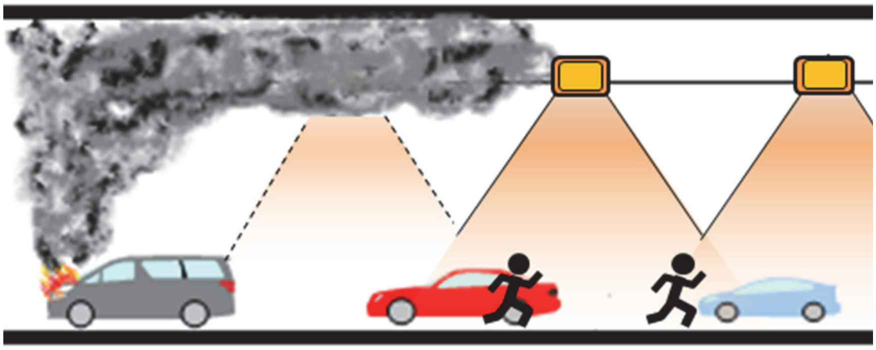
(ii) Communication by other evacuees

Nillson etc. [33] reported regarding evacuation behavior using a full scale tunnel there existed a tendency that people felt the necessity of evacuation when they saw the evacuating people. Based on this report, evacuees recognize the necessity of evacuation when other evacuees arrive to them in 15 m (see Fig. 11 (ii)).

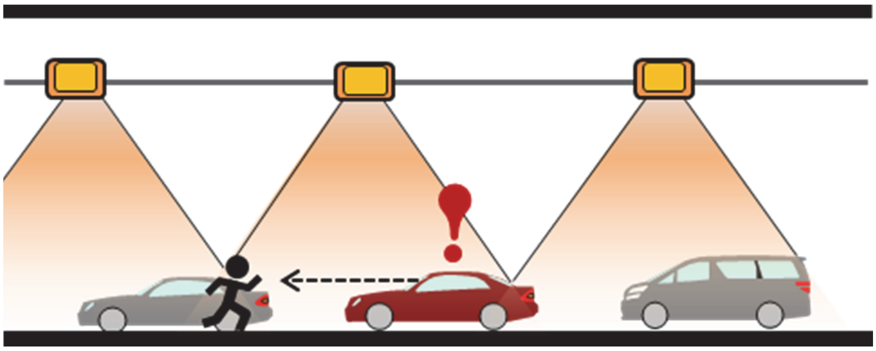
(iii) Information by the outside (emergency announcement)

In the case of emergency announcement facilities installed, evacuees recognize the necessity of evacuation after the emergency announcement (see Fig. 11 (iii)).

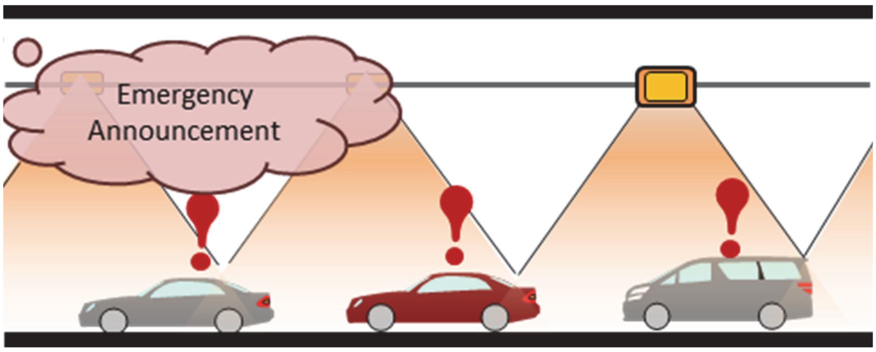
After recognizing the necessity of evacuation, there is time lag to prepare to evacuation before evacuees start to evacuate. The time lag is defined the pre-starting time of evacuation, which is between 5 s to 15 s in the present paper by random numbers used in each evacuees.



(i) Phenomena around evacuees (smoke along the ceiling)



(ii) Communication by other evacuees



(iii) Information by the outside (emergency announcement)

Fig. 11 Reorganization evacuation necessity model

4.3 Evacuation walking speed model

Evacuation walking speeds is determined by situation of smoke around the evacuees, that is SE levels. The relation between smoke optical density and evacuation walking speed reported by Jin [34] is famous, investigation of the prevention disaster of tunnel fires in Japan is also used based on Jin's results, so that SE level 4 (Cs = 0.4 m^{-1} at z = 1.5 m) is the situation when evacuees are surrounded by smoke and stop evacuation, evacuation walking speed v = 0 m/s.

Evacuation walking speed depending on their age, gender, etc., that is, the individual difference is large. To assign different evacuation walking speed to each evacuees, evacuation walking speed distribution is indicated in Fig. 11, the horizontal axis indicates the evacuation walking speed v and the vertical axis indicates probability distribution of evacuation walking speed S, integration by v of S is determined 1 by normalization.

$$\int_0^{\infty} S dv = 1 \tag{3}$$

4 cases in Fig. 12 indicate based on reasons as follows. Case 1 is determined by consideration that mean of evacuation walking speed 1.3 m/s is based on the reference[35], the minimum of evacuation walking speed is 1 m/s, which is generally adopted on tunnel fire safety, the evacuation walking speed range is from 0.9 m/s to 1.7 m/s. Case 2 is determined on the reference [36], mean of evacuation walking speed 1.33 m/s, fast walking speed 2 m/s. Cases 1 and 2 are based on the general walking speed measures. Case 3 is supposed the hurry situation, mean of walking speed 1.5 m/s during morning commuting hours on The Architectural Institute of Japan, Handbook of Environmental Design [37], and used the same idea as case 1. More serious situation is in case 4, Bore [38] measured evacuation walking speed, whom explained that there was in a danger of explosion and they must evacuate immediately etc., used the actual tunnel, as a consequence, mean of speed 2.3 m/s, maximum of speed 3.1 m/s were obtained. Case 4 is determined by referring the consequents.

To determine evacuation walking speed to each evacuees, random number (0 to 1) is given to each evacuees. An evacuees random number r_i, where the suffix i indicates a evacuees' number, and his evacuation walking speed v_i are related as follows:

$$r_i = \int_0^{v_i} S dv \tag{4}$$

v_i at r_i given by equation (4) is calculated numerically. Additionally, drivers are considered not included children and elderly people, a driver's r_i indicates as follows:

$$0.9r_i + 0.1 \tag{5}$$

Driver's r_i range is change from 0.1 to 1 like eq. (5), drivers' evacuation walking speed is determined excepting the slow side of 10 % range (left side) of evacuation walking speed in Fig. 12. Here, 10 % is given by considering Japanese population ratio of children and elderly people.

In the present paper, evacuees finish evacuating when evacuees arrive in 10 m from emergency exits or portals.

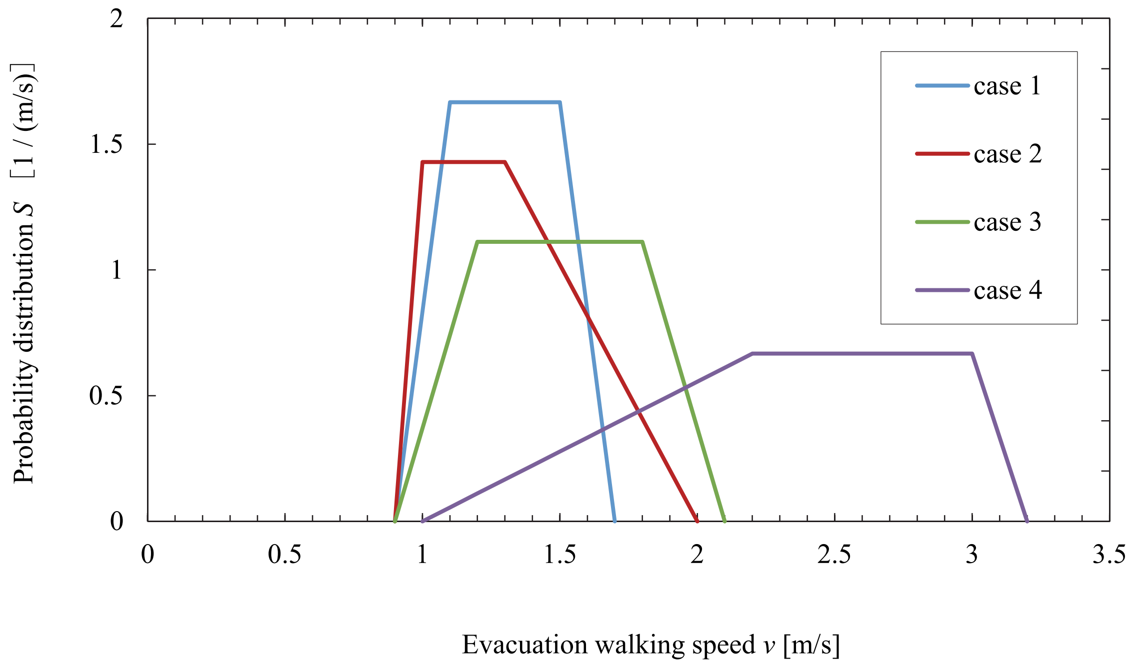


Fig. 12 Evacuation walking speed distribution

4.4 Evacuees behavior map

Drawn the black solid lines of changes in each evacuees' location on smoke environment map, to indicate smoke behavior and evacuees activities can show in the same time. This figure is defined evacuees behavior map, and one example in the case of g = 2% in chapter 3.2 indicates in Fig. 13. Evacuees A to D are arranged from 10 m to each 100 m from the fire source, range between 1.0 to 1.3 m/s of evacuation walking speed of each evacuees is determined by random number, emergency announcement is undertaken after 3 min from the ignition.

Evacuee A at 10 m from the fire source starts evacuating by seeing the smoke along the ceiling (SE level 1) after 1 min (see Fig. 13). Evacuee A's evacuation walking speed is faster than smoke tip propagating velocity, evacuee A can evacuate safely, and arrives near evacuee B in around 2 min. Evacuee B starts to evacuate by seeing evacuee A, but evacuee B's walking speed is later than evacuee A's and evacuee B is the latest. Evacuees C and D start to evacuate in 3 min by the emergency announcement, and arrive the right portal earlier than evacuee A. Smoke tip propagating velocity increases with fire developing, smoke spreads to the floor, as a results, evacuee B cannot evacuate due to surrounded by smoke at around 50 m from the right portal. Evacuee A arrives the right portal at the same time when smoke arrives the right portal, can finish evacuation safely. Therefore, smoke behavior and evacuees' activities with every moment can be seen perfectly in evacuees behavior map.

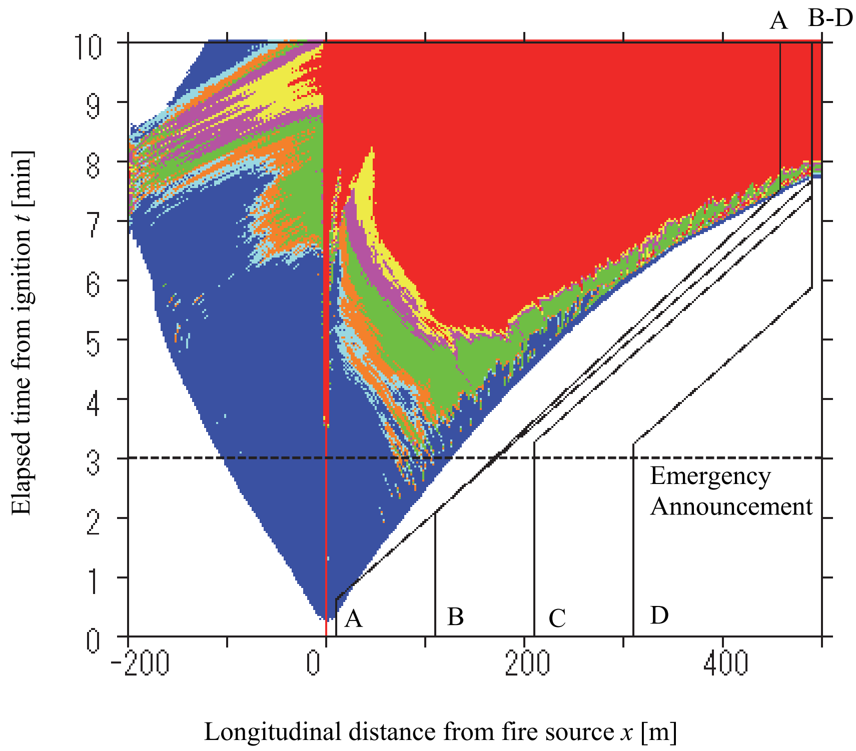


Fig. 13 Evacuees behavior map

4.5 Mean of a Number of People Requiring Help

In an assessment time (10 min in the present study) from ignition, evacuees who are surrounded by smoke and cannot evacuate safely, are defined as sufferers, a Number of People Requiring Help (NPRH) are used as indicator of assessment for tunnel fire safety in the present paper. In investigation of actual cases, the number of traffic jam vehicles is determined based on traffic volume and mix rate of heavy goods vehicles, however, was taken simplification in the present paper, all traffic jam vehicles are passenger cars (4 m in length), the distance between a car and the one in front is 2 m, both lanes are filled with traffic jam space headway of 6 m from fire source to the right portal. Mean of number of the passenger per car is 1.4 passenger/car [39], the rate of the number of passengers is determined as 70 % in the case of only a driver, 20 % in the case of 2 passengers and 10 % in the case of 3 passengers by using random number, which different each calculating cases, so that NPRH in the same situation is also different each simulations. The total number of passenger cars is 163, so that the total number of evacuees is around 228. The present study's scenario is that a volume of traffic is 2500 pcu / hour (passenger car unit per hour) [40], in two minutes when a fire vehicle stops fire point, traffic jam occurs from fire point to right tunnel exit. Assessing for fire accidents, maximum of damage is often supposed, but the present study suggests the assessment using mean of damage, mean of NPRH averaged many simulation results is used.

Fig. 14 shows horizontal axis taken as simulation count, dots as NPRH and continuous line as mean of NPRH in the case of g = 4 %. NPRH distributed the range between 7 to 34 people, the mean of NPRH is 19.05 people from Fig. 14. Additionally, mean of NPRH fluctuates when counts are small, but counts increasing, fluctuation becomes small gradually and finally almost constant. In the present study, the one dimensional evacuation simulation is adopted, that is, calculating time is extremely fast, so that the results in the present paper as follows are used as mean of value of 1000 times. This constant value is defined as the mean of NPRH.

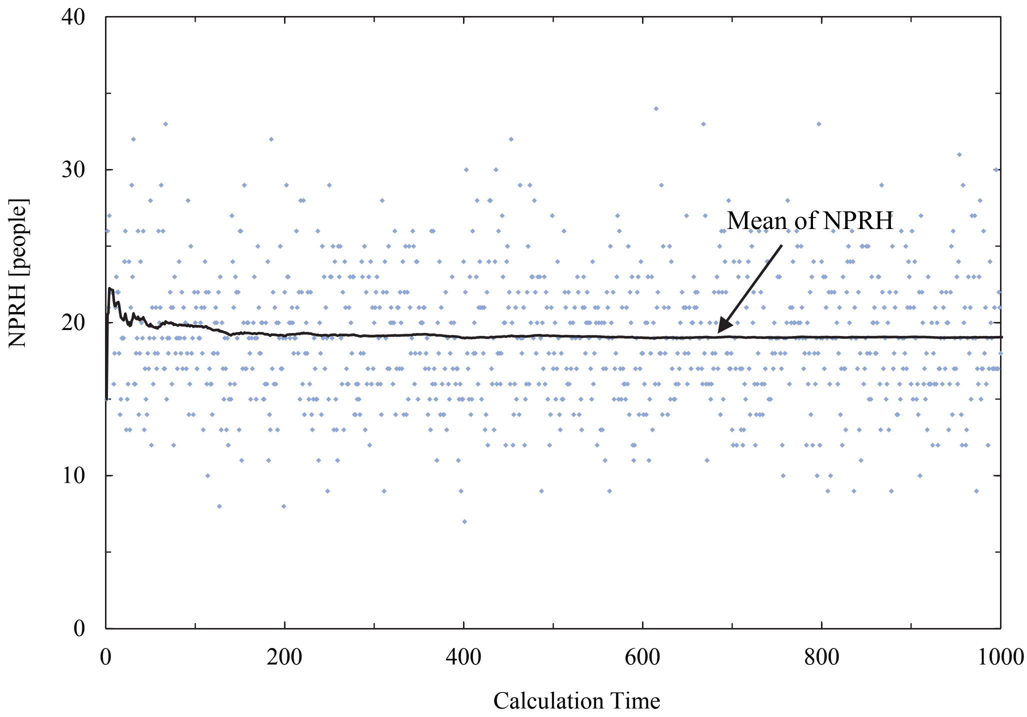


Fig. 14 Mean of NPRH (g = 4%)

4.6 Summary

In the present chapter, to develop the evacuation behavior model in tunnel fires, at first past studies treated evacuation inside buildings and huge disasters are investigated. Secondly, evacuation model in smoke of tunnel fires were developed. Main results are as follows;

1. Considering smoke behavior inside tunnels made a great impact on evacuees' behavior, smoke behavior consists complicated behavior in tunnels with gradient, natural ventilation, application of ventilation facilities, heat release rate scale, etc., moreover, evacuation under the smoke layer has to be supposed, hence evacuation behavior simulation using smoke behavior detailed analysis is necessary. In the present paper, using SE levels in chapter 3 by 3-D LES-CFD analysis in chapter 2, the evacuation behavior simulation considered smoke optical density is suggested. Evacuees' behavior does not influence to smoke behavior, so that evacuation behavior simulation in the present paper becomes 1-way coupling to CFD analysis of smoke behavior.
2. The present suggested evacuation behavior model is chasing each evacuees' behavior, and considering each evacuees' phenomenon occurred in evacuating. Tunnel spaces are extremely long comparing with wide length, but having around 10 m wide, so that tunnels are huge, enclosed and unique. Meanwhile, tunnel users existing concentratedly in a place are seldom, but are dotted with traffic jam sections. Therefore, when evacuees go through roadways where become evacuation passages in emergency situation, even if there are vehicles stopped, it can be considered that evacuees can go through the side easily, influence of physical interference between evacuees is disregard, so that it is defined that evacuees can pass the others. Also evacuees can recognize the longitudinal direction of tunnel and to lose sight of the evacuation direction is not considered, so that evacuation behavior is treated one-dimensional behavior limited to longitudinal x direction.
3. The factors to recognize the necessity of evacuation are determined phenomena around evacuees, communication by other evacuees and information by the outside, which are phenomena around evacuees (smoke along the ceiling), Communication by other evacuees and Information by the outside (emergency announcement).

4. Evacuation walking speeds is determined by situation of smoke around the evacuees, that is SE levels. Investigation of the prevention disaster of tunnel fires in Japan is also used based on Jin's results [17], so that SE level 4 (Cs = 0.4 m^{-1} at z = 1.5 m) is the situation when evacuees are surrounded by smoke and stop evacuation, evacuation walking speed v = 0 m/s.
5. Evacuation walking speed curves are determined by each references. Case 1 is determined by consideration that mean of evacuation walking speed 1.3 m/s is based on the reference [35], the minimum of evacuation walking speed is 1 m/s, which is generally adopted on tunnel fire safety, the evacuation walking speed range is from 0.9 m/s to 1.7 m/s. Case 2 is determined on the reference [36], mean of evacuation walking speed 1.33 m/s, fast walking speed 2 m/s. Cases 1 and 2 are based on the general walking speed measures. Case 3 is supposed the hurry situation, mean of walking speed 1.5 m/s during morning commuting hours on The Architectural Institute of Japan, Handbook of Environmental Design [37], and used the same idea as case 1. More serious situation is in case 4, Bore [38] measured evacuation walking speed, whom explained that there was in a danger of explosion and they must evacuate immediately etc., used the actual tunnel, as a consequence, mean of speed 2.3 m/s, maximum of speed 3.1 m/s were obtained.
6. Drawn the black solid lines of changes in each evacuees' location on smoke environment map, to indicate smoke behavior and evacuees activities can show in the same time, which is defined as evacuees behavior map. Investigating evacuees behavior map, smoke behavior and evacuees' activities with every moment can be seen perfectly in evacuees behavior map.
7. In an assessment time (10 min in the present study) from ignition, evacuees who are surrounded by smoke and cannot evacuate safely, are defined as sufferers, a Number of People Requiring Help (NPRH) are used as indicator of assessment for tunnel fire safety in the present paper. In the present paper as follows are used as mean of value of 1000 times.

5. CALCULATION EXAMPLE

5.1 Influence of longitudinal gradient and evacuation walking speed

The mean of NPRH in cases of 1 to 4 of evacuation walking speed in Fig. 12 is shown in Fig. 15, horizontal axis is tunnel longitudinal gradient g and vertical axis is the mean of NPRH, influence of the tunnel fire safety by longitudinal gradient is investigated. Fig. 16 shows evacuees behavior map of cases 1 to 4 of evacuation walking speed, which is late in case 1(see Fig. 16 (i)) and fast in case 4(see Fig. 16 (iv)), in the case of g = 4 %. In Japan tunnels of 700 m in length are not installed emergency announcement generally, so that Figs 15 and 16 are assumed no emergency announcement.

In Fig. 15, it can be seen that in cases 1 and 2 as general walking speed sufferers increases from g = 1 %, increases quadratically with increasing g and are around 20 people in g = 4 %. Possibly because smoke tip propagating velocity increases with gradient increasing, so that evacuees surrounded by smoke increase. In case 3 supposed hurry situation, sufferers start to increase from g = 2 % gradually, and are less than 6 people in g = 4 %, that is, smaller than cases 1 and 2. In case 4 supposed the most serious situation, communication to the users in tunnel is fast (see Fig. 16 (iv)), so that no sufferer exists even if gradient increases. Consequently, evacuation walking speed is huge influence to NPRH, especially maximum of evacuation walking speed being large is effective to make communication to the users in tunnel fast, so that it is possibly considered that NPRH reduces. Hence, it was found that communication immediately to the users in tunnel was important.

One method of immediate communication is emergency announcement. Fig. 17 shows emergency announcement timing effect, which horizontal axis is emergency announcement time from ignition and vertical axis is mean of NPRH. The continuous line is undertaken emergency announcement, and the dotted line is no emergency announcement. Case 2 of late evacuation walking speed, g = 4 % and other condition same as Fig. 16 is indicated in Fig. 17. It can be seen that mean of NPRH in the case of no emergency announcement is around 22 people, meanwhile, when emergency announcement is undertaken at 60 s from ignition, mean of NPRH is around 15 people, and reduced 7 people comparing no emergency announcement. Additionally, at 90 s of emergency announcement, only a little over 2 people reduces, therefore it was found that emergency announcement is preferable in 60 s from ignition. In this case, it is considered that smoke tip propagating velocity becomes large influenced by buoyancy short tunnel of 700 m in length, so that emergency announcement effect becomes small.

In the present chapter, one of examples of assessment used NPRH is indicated, so that it was found that influences by evacuation walking speed and longitudinal gradient, and effect of emergency announcement timing is possible to quantify and compare. For reference, Evacuees behavior map in each cases of emergency announcement time in Fig. 18.

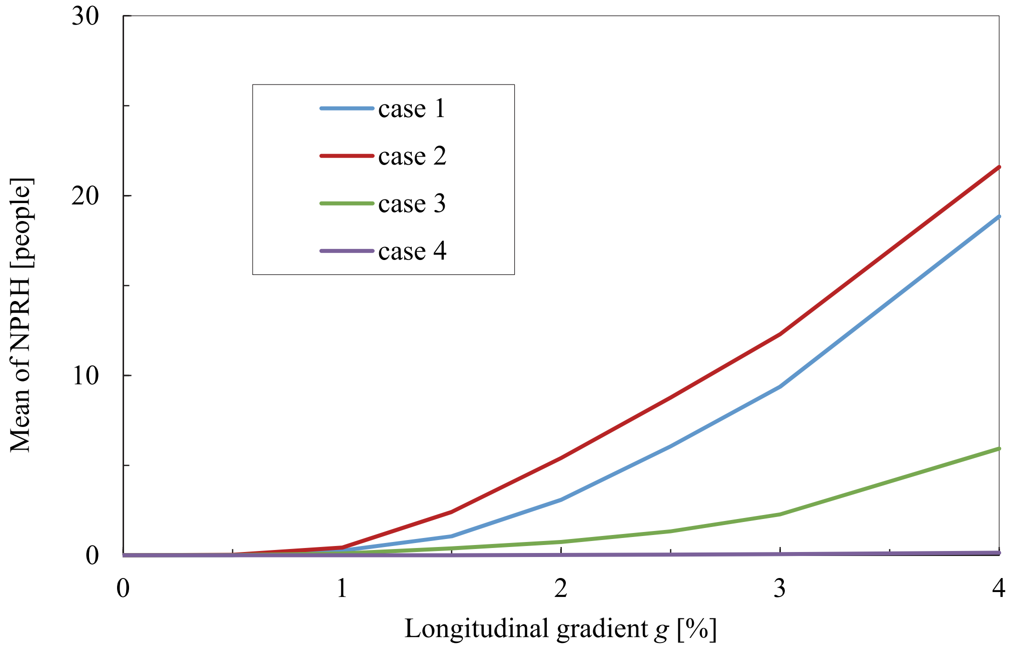
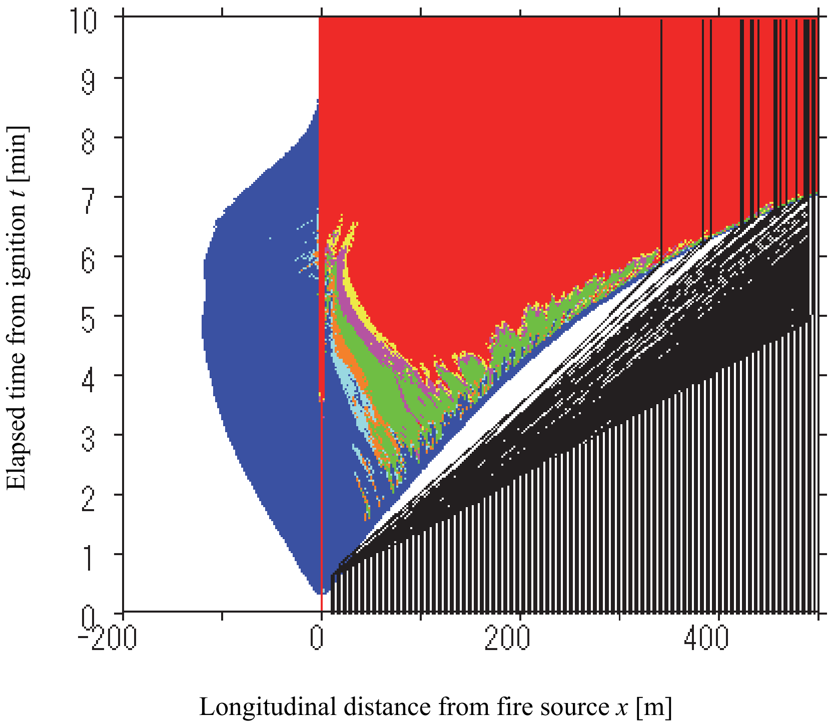
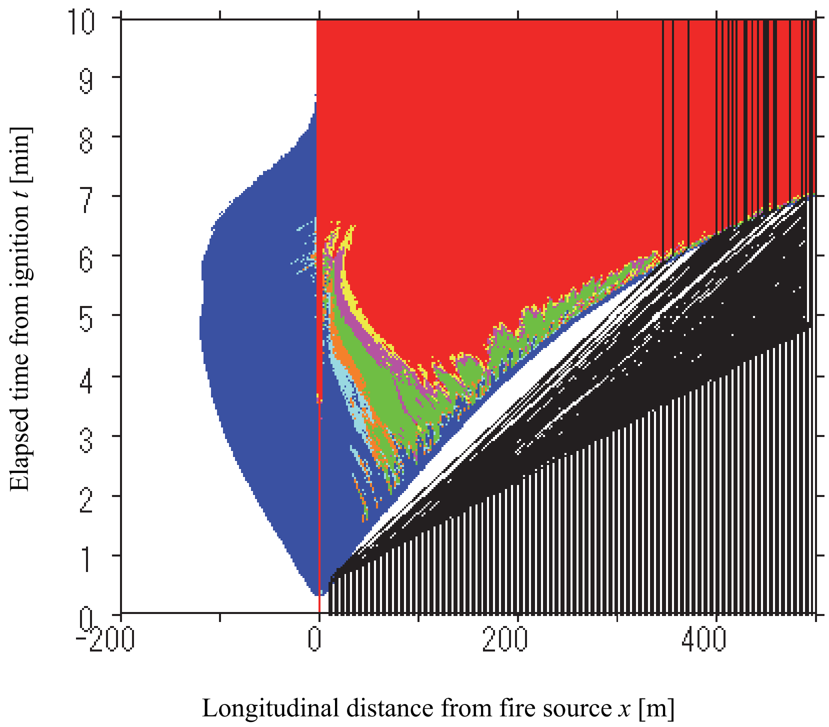


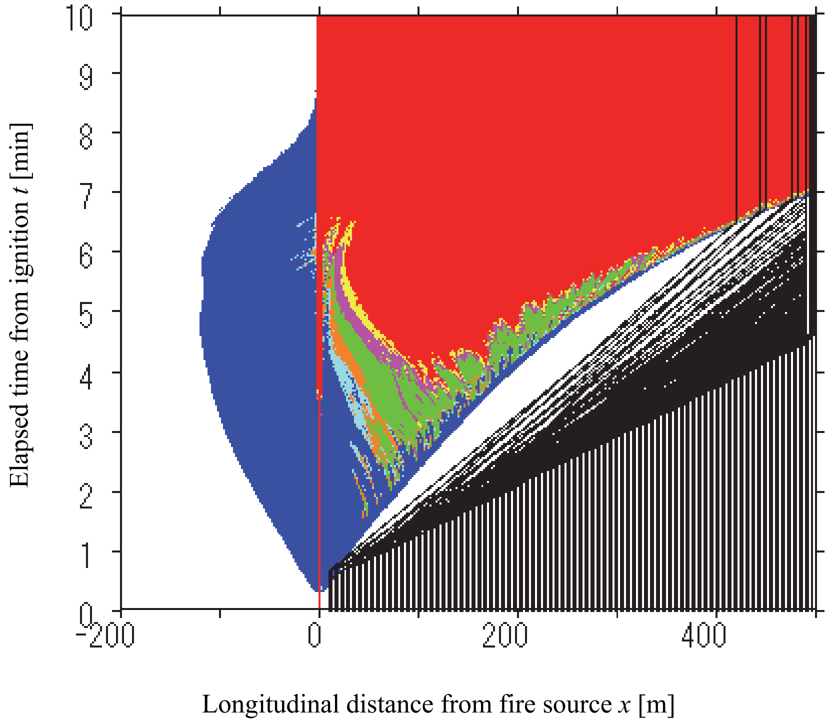
Fig. 15 Influence of longitudinal gradient



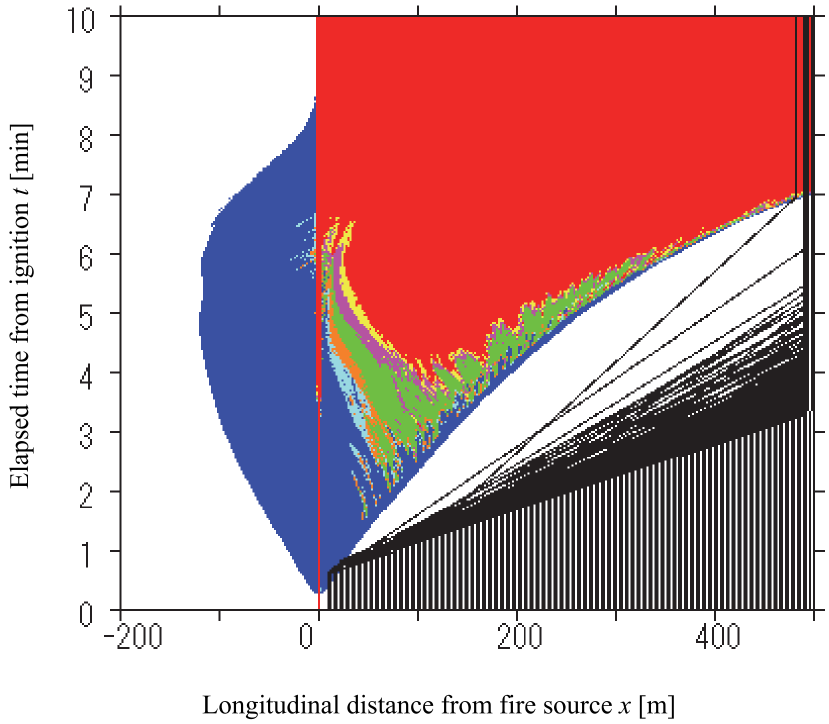
(i) case 1



(ii) case 2



(iii) case 3



(iv) case 4

Fig. 16 Evacuees behavior map (the differences from each evacuation walking speed)

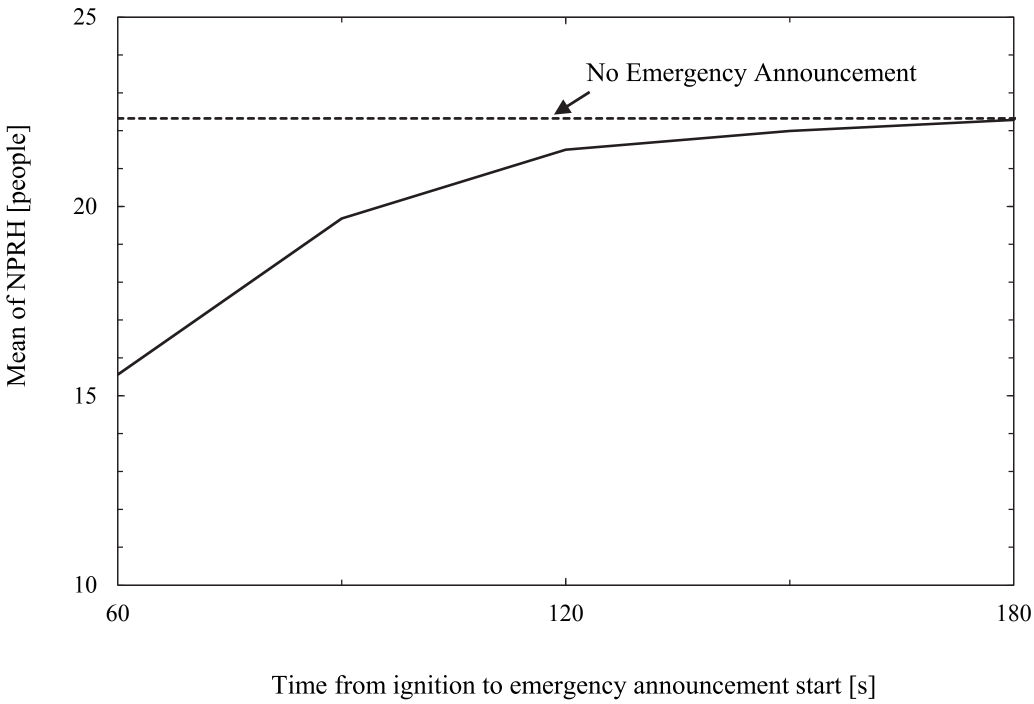
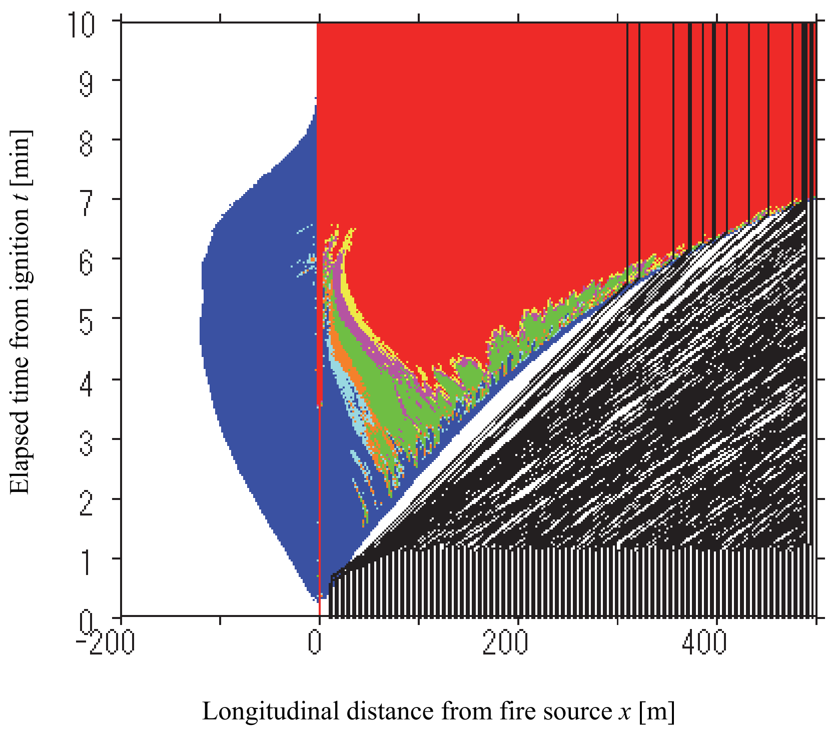
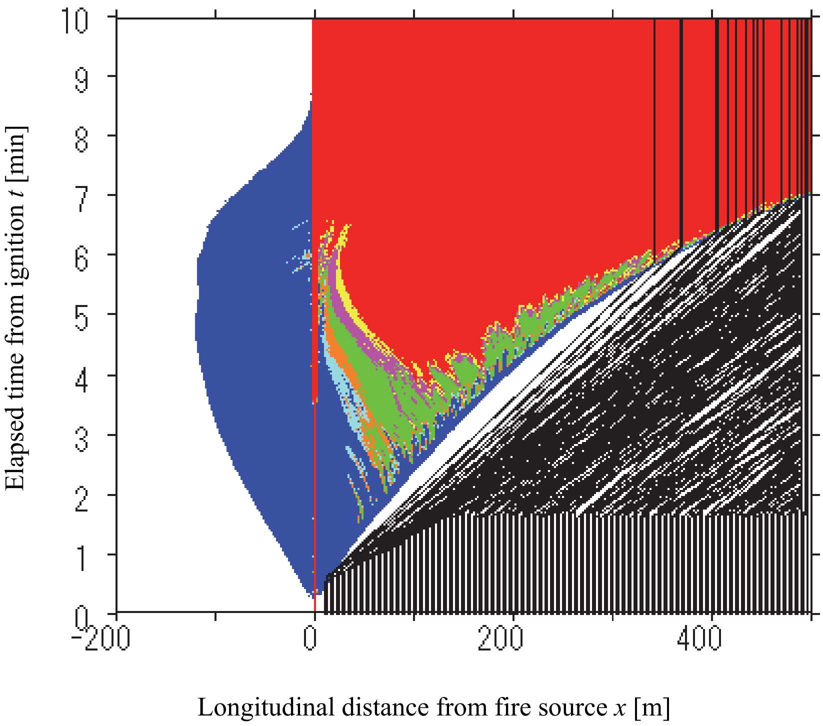


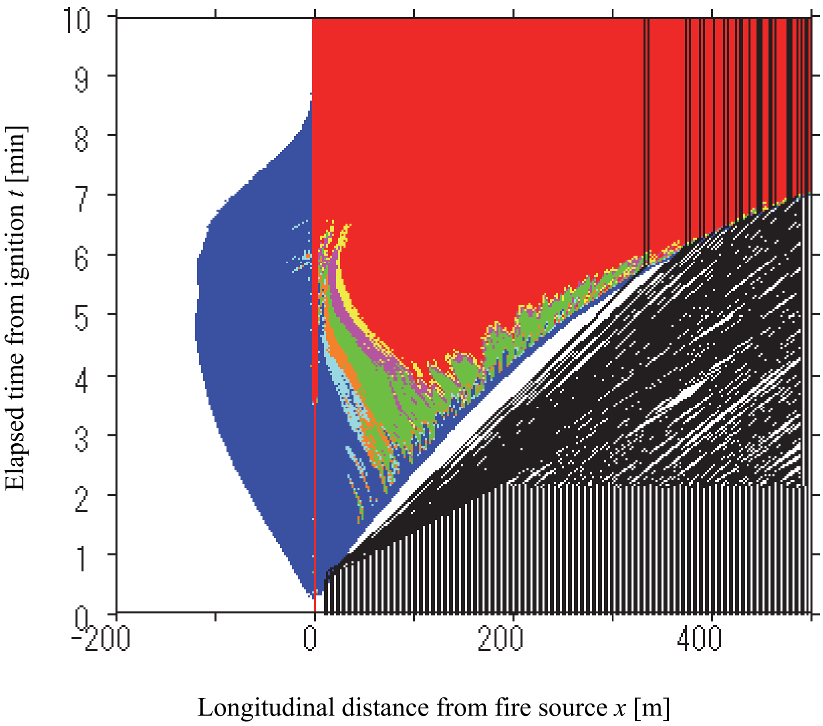
Fig. 17 Effect of emergency announcement time (Case 2, $g = 4\%$)



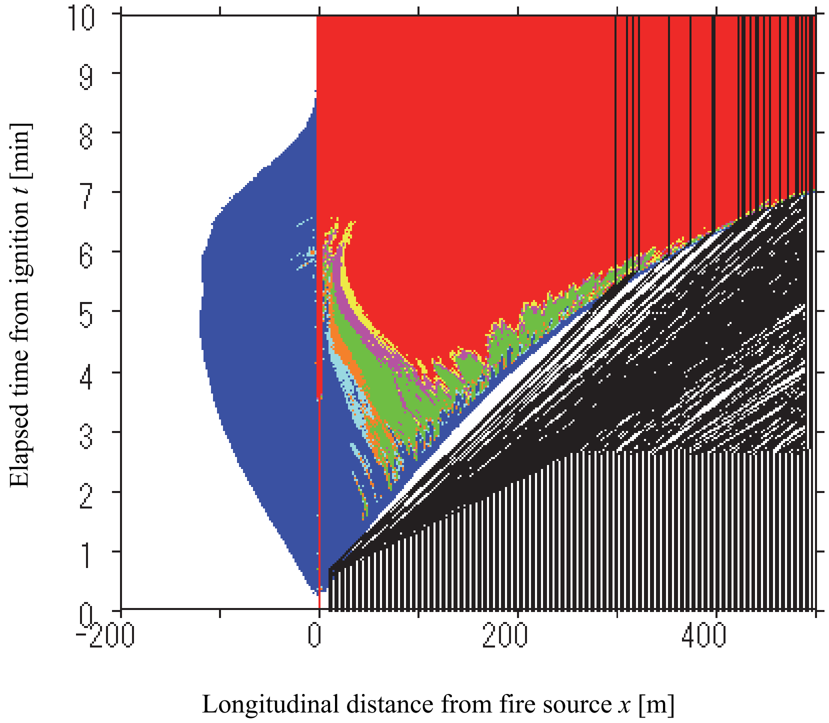
(i) 60 s



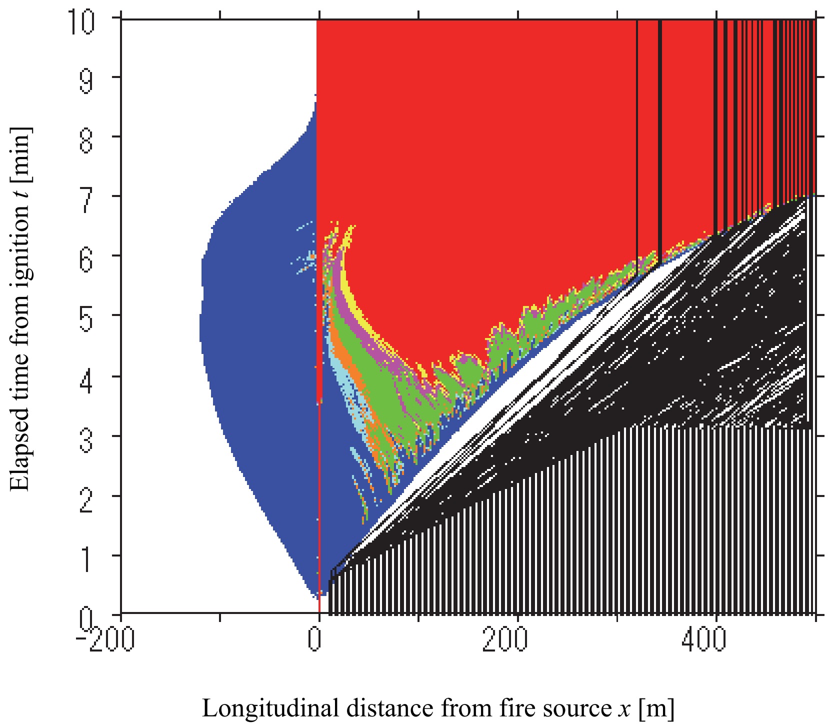
(ii) 90 s



(ii) 120 s



(ii) 150 s



(ii) 180 s

Fig. 18 Effect of each emergency announcement (Case 2, $g = 4\%$)

5.2 Influence of heat release rate and smoke generation rate

5.2.1 Geometry and condition

Fire accident occurred in 200 meters (x = 0 m) from left exit. Traffic jam occurred to the right portal (x = 500 m) from the fire source (x = 0 m). The positive direction from left to right portals was defined. x was the distance from the fire point to right direction (the origin was x = 0 m).

Maximum of convective heat release rate of 20 MW [18] and max smoke particles generation rate of 90 g/s [19] were obtained as same as section *2.3.2*, and the basic case was determined maximum of convective heat release rate arriving at 8 minutes from fire ignition, indicates q08. Additionally the cases that maximum of heat release rate becomes at 9 minutes to 12 minutes indicate each of q09 to q12, and influence of heat release rate time profile to tunnel fire safety was investigated in the present section (see Fig. 19). Smoke generation rate curve was adopted the same curve as q08, maximum of smoke generation rate changes to 30 g/s to 90 g/s and the each cases indicate s30 to s90. Evacuation walking speed was adopted case 3 in Fig. 12.

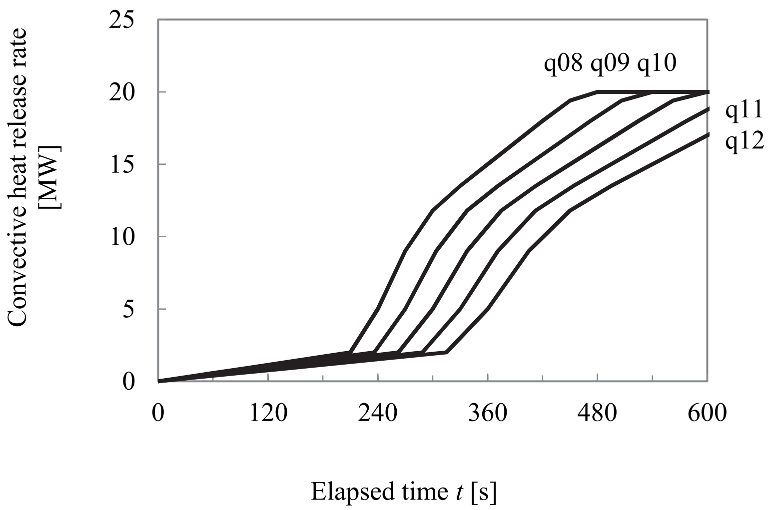


Fig. 19 Convective heat release rate

5.2.2 Influence of heat release rate and smoke generation rate

Fig. 20 shows the influence of heat release rate to tunnel fire safety in the case of g = 1.5 %, vertical axis is mean of NPRH and horizontal axis is cases of heat release rate. Fig. 20 indicates that there exists big influence to tunnel fire safety by the start of heat release rate. Fig. 21 shows the influence of maximum smoke generation rate to tunnel fire safety in the case of g = 1.5 %, vertical axis is mean of NPRH and horizontal axis is cases of maximum smoke generation rate. Comparing between s30 and s90, it can be seen that mean of NPRH in s30 is more than in s90 in Fig. 21. This is because evacuees delay to start due to reducing smoke generation volume, so that NPRH does not decreased even if reducing smoke generation volume. For reference, Evacuees behavior map in each cases of convective heat release rate and maximum of smoke generation rate in Figs. 22 and 23.

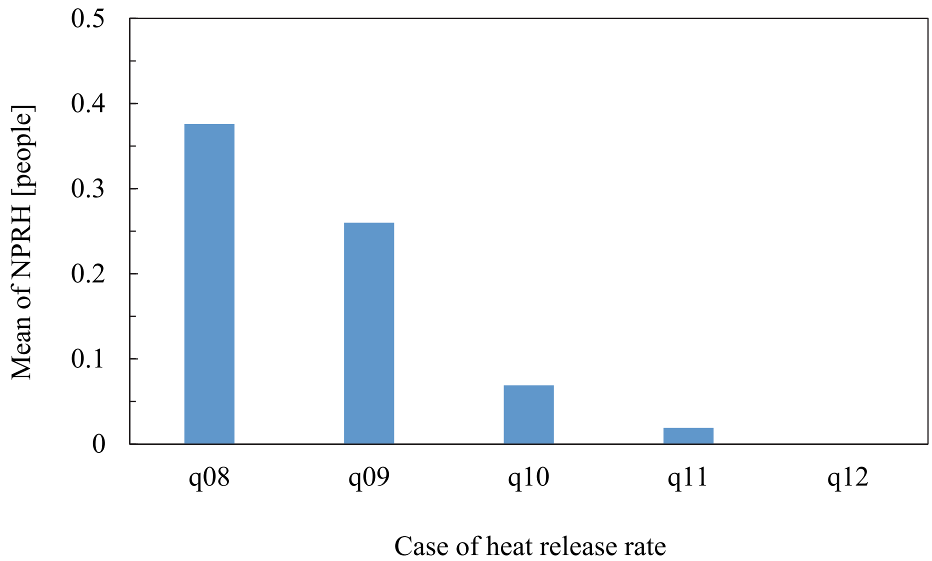


Fig. 20 Influence of heat release rate curve (g = 1.5 %)

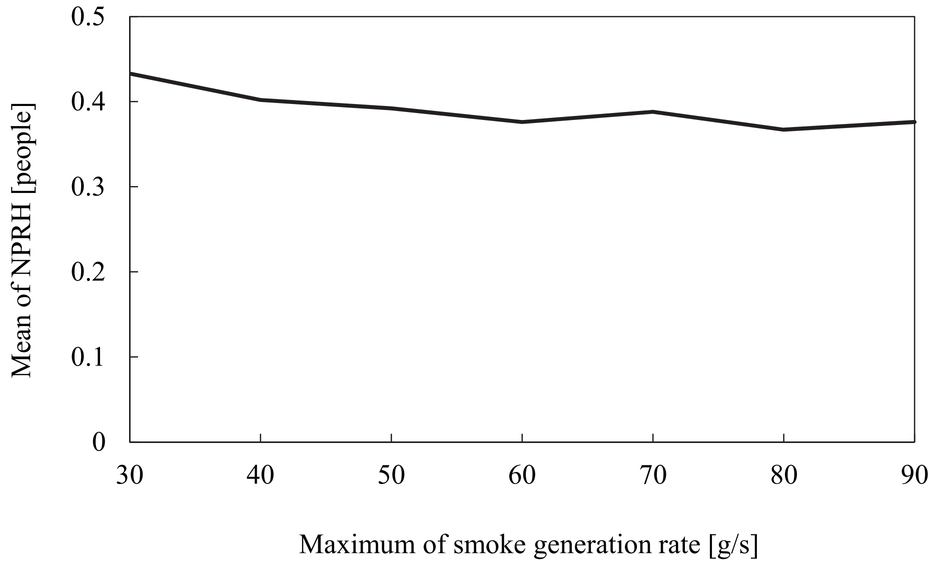
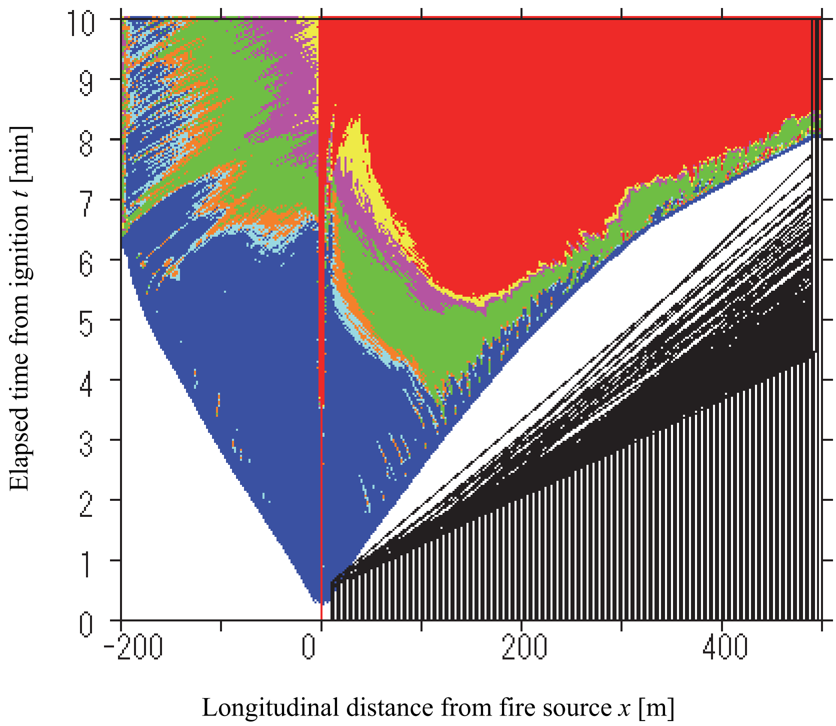
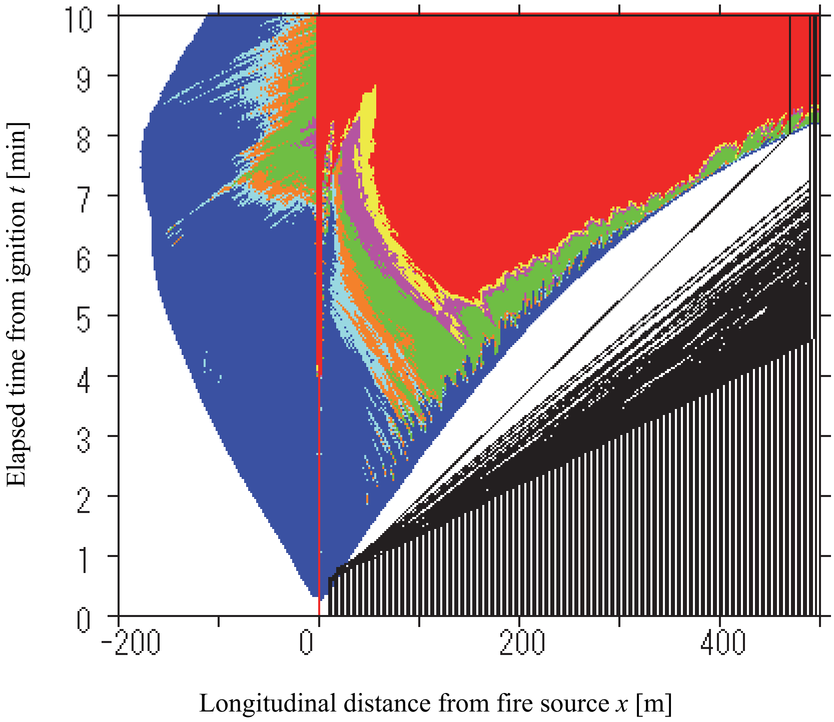


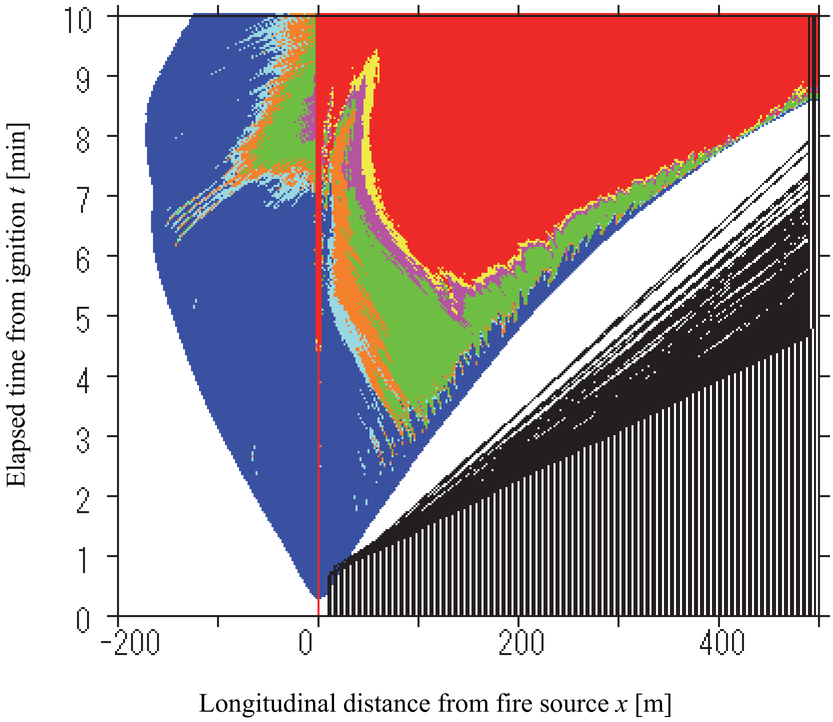
Fig. 21 Influence of maximum of smoke generation rate (g = 1.5 %)



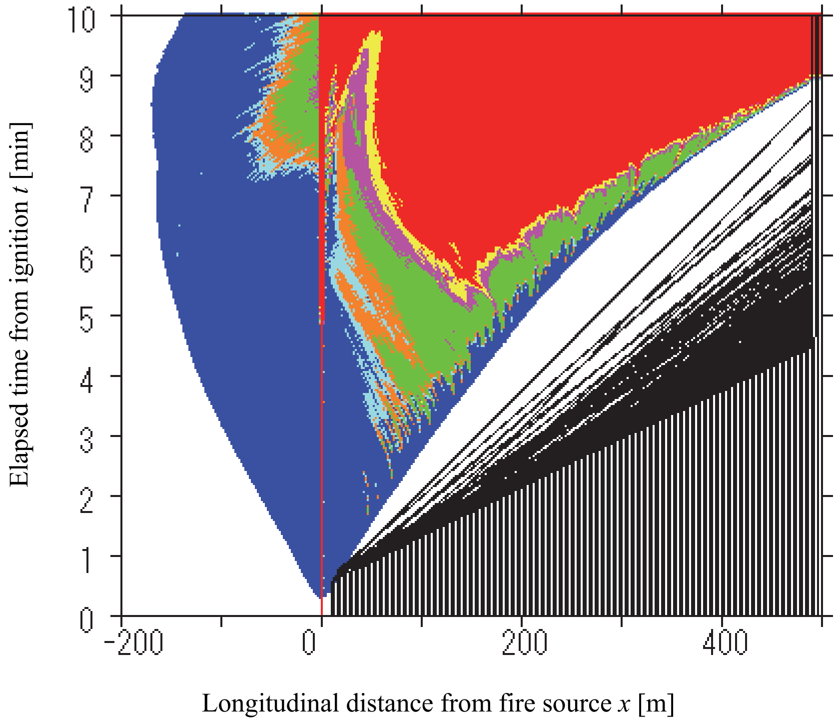
(i) q08



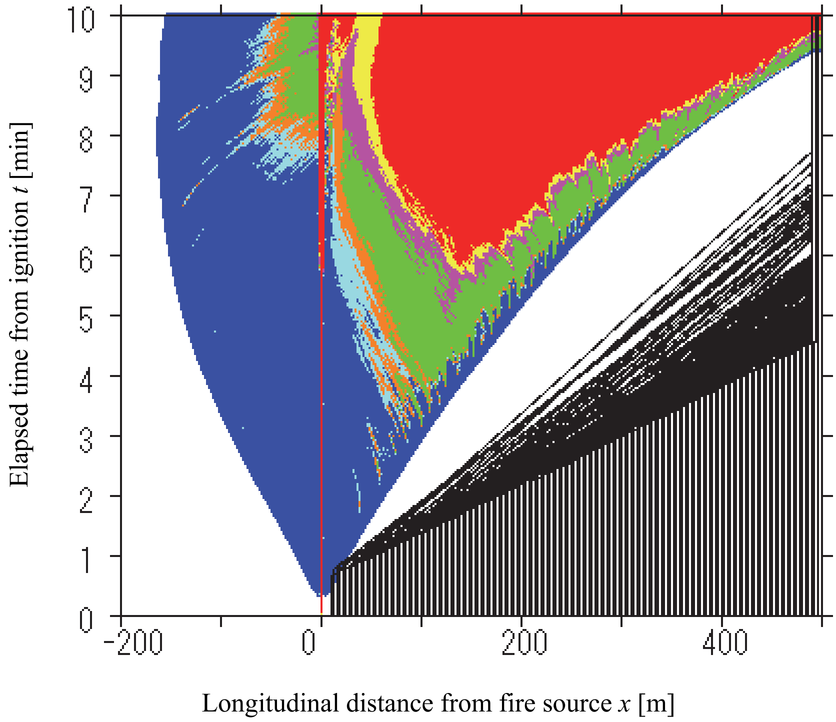
(ii) q09



(iii) q10


10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Elapsed time from ignition t [min]
Longitudinal distance from fire source x [m]

(iv) q11

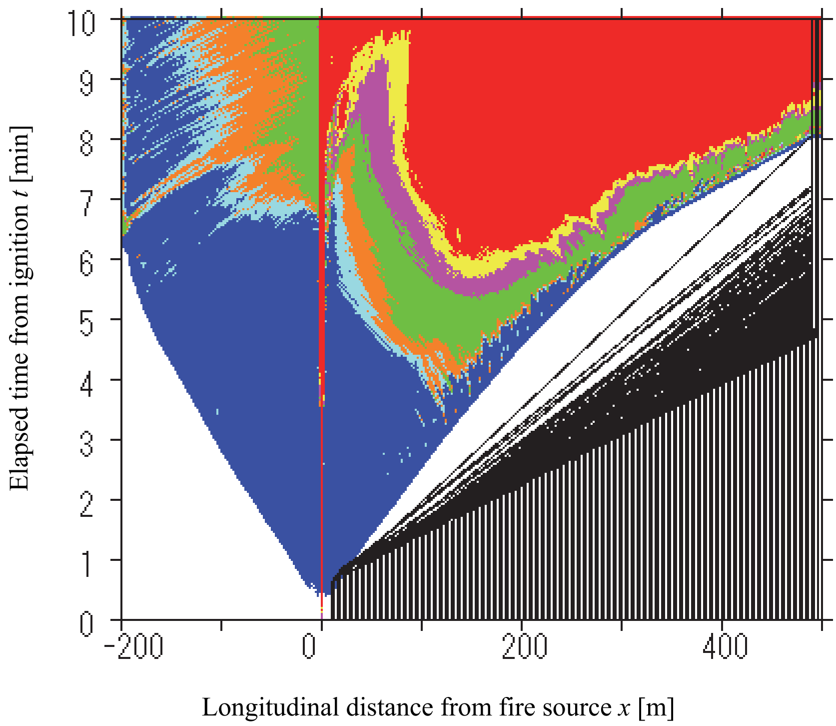


(v) q12

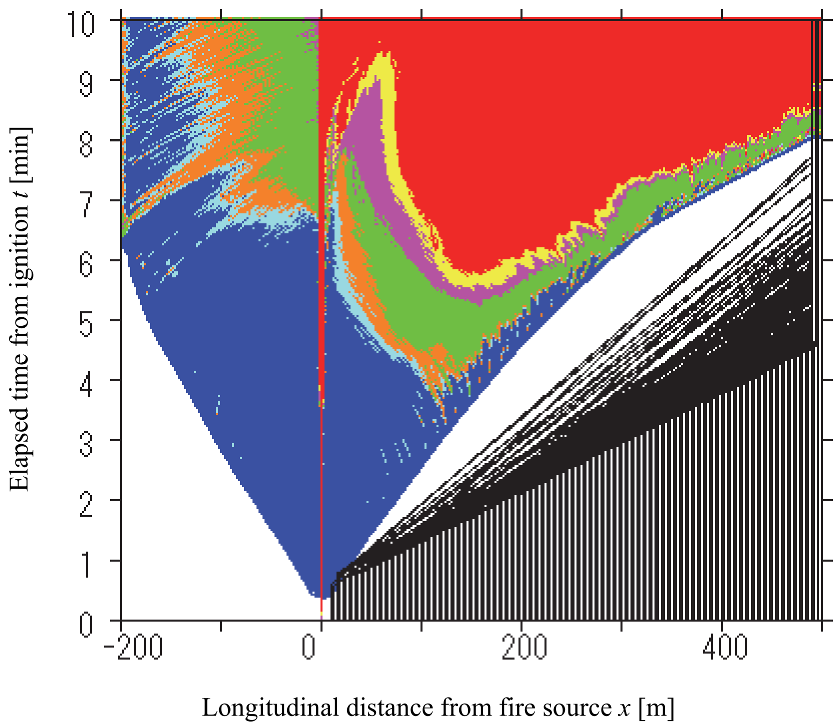
Fig. 22 Evacuees behavior map

Influence of convective heat release rate

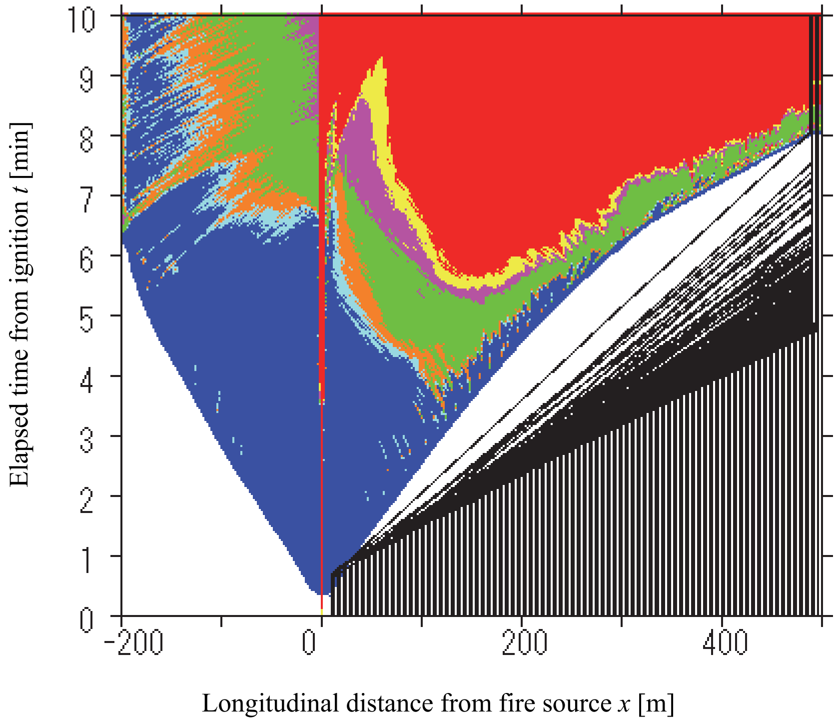
(g = 1.5 %)


Elapsed time from ignition t [min]
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Longitudinal distance from fire source x [m]

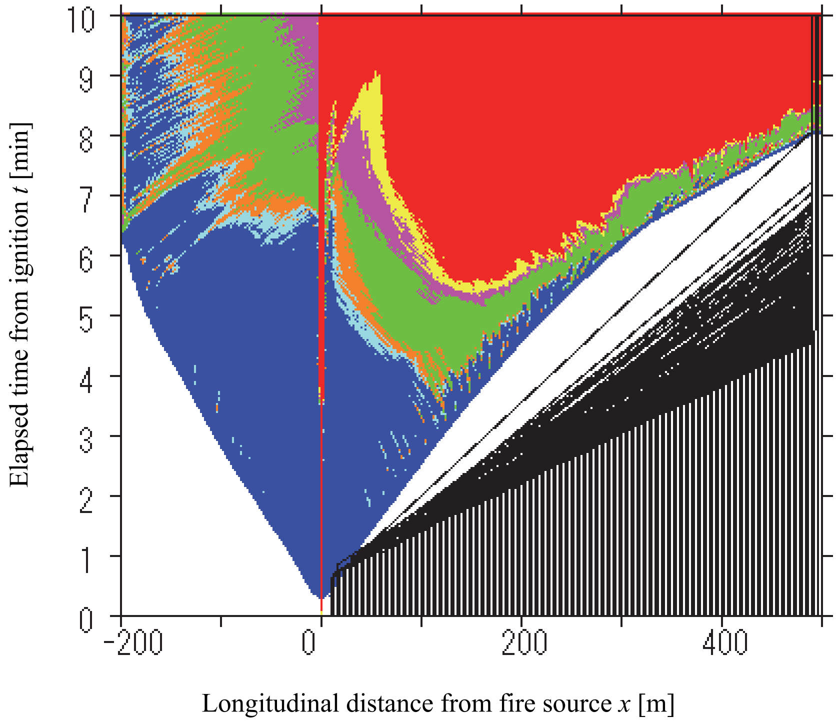
(i) s30


Elapsed time from ignition t [min]
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Longitudinal distance from fire source x [m]

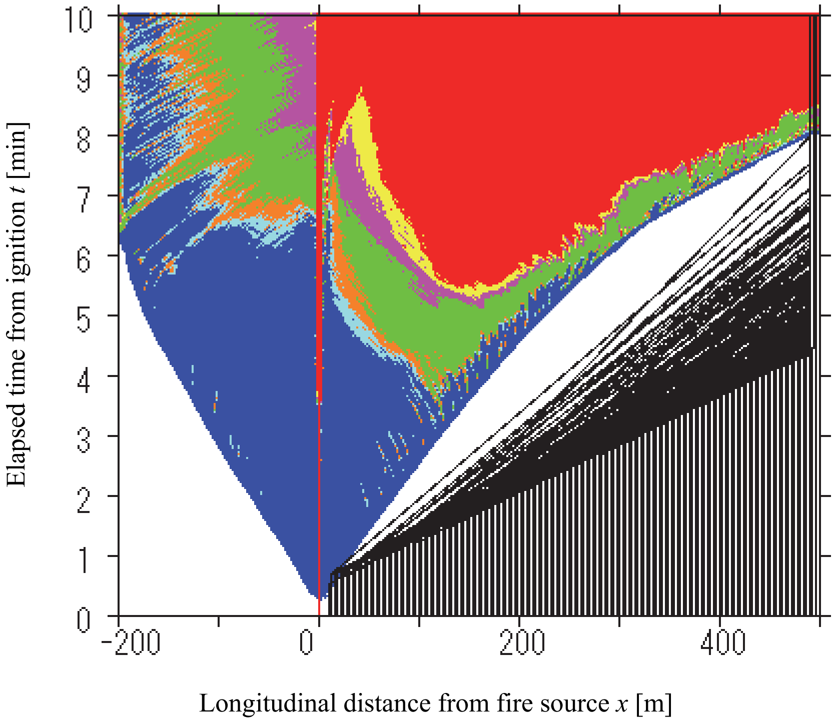
(ii) s40



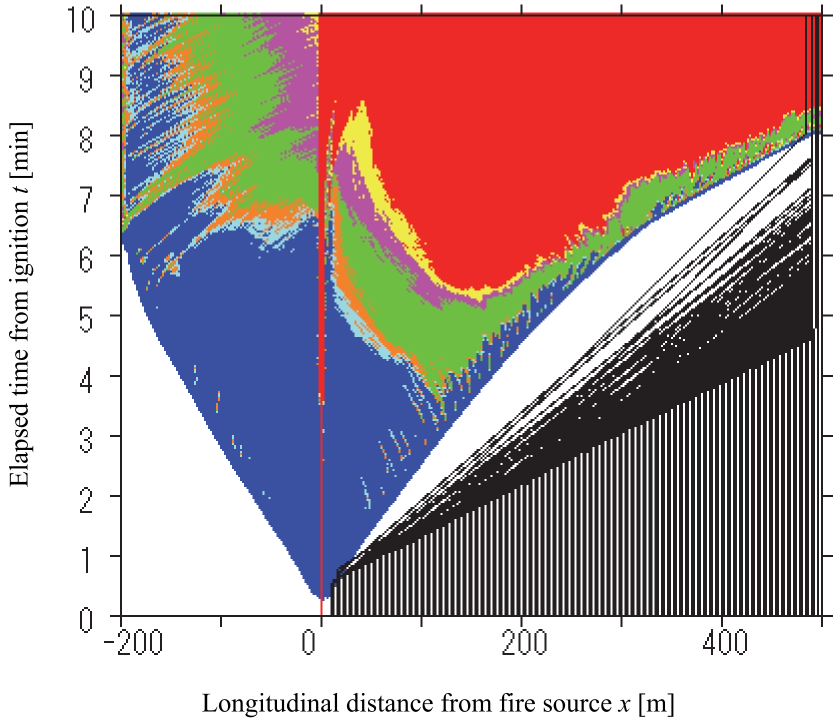
(iii) s50



(iv) s60


Elapsed time from ignition t [min]
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
Longitudinal distance from fire source x [m]

(v) s70



(vi) s80

Fig. 23 Evacuees behavior map

Influence of maximum of smoke generation rate

(g = 1.5 %)

5.3 Influence of tunnel length

5.3.1 Tunnel length and gradient

Table 2 shows that conditions in this study. A vertical section of a model tunnel in this study is a rectangle and the tunnel is two lanes and uni-direction. x was determined as the longitudinal direction and the origin was the fire point. The gradient was uphill to the positive direction of x. Congestions occurred in the right side by the fire and the congestions consisted of small and large vehicles. Evacuation walking speed was adopted case 3 in Fig. 12. Model tunnel was adopted a rectangular section, as same as in chapter 2, 5 meters height, 10 meters width, two-lane and one-way (see Fig. 24).

The total number of passenger cars is 48(67 people) at L = 500 m, 121(139 people) at L =700 m, 217 (246 people) at L = 1000 m, 371 (423 people) at L = 1500 m and 527 (602 people) at L = 2000 m respectively.

Table 2. Conditions

Tunnel geometry (Length (L) ×Width (W) × Height(H))	500 – 2000 m × 10 m × 5 m
Fire point	300 m from the left portal (x = 0 m)
Mixing ration of large vehicle	10 %
Average of a number of passengers by vehicle (people)	Small vehicle: 1.4
	Large vehicle: 1.3
Measurement of 3 small vehicles	L_{small} = 12 m, W_{small} = 1.7 m, H_{small} = 1.6 m
Measurement of a large vehicle	L_{large} = 8 m, W_{large} = 2.6 m, H_{large} = 2.8 m
Vehicular gap	4 m

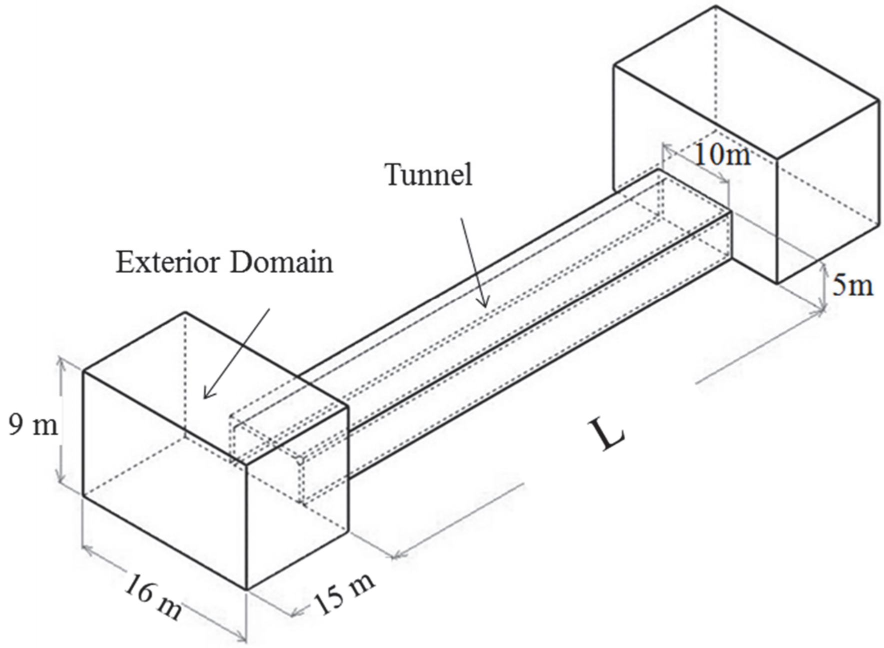


Fig. 24 Reorganization evacuation necessity model

Fig. 25 indicates that influence of tunnel length (L) and gradient (g) in tunnel fire. In the case of g = 0 to 1 %, NPRH was 0 independently of L, however, in the case of g = 2 %, NPRH increased between L = 1000 and 1500 m. because a total of mass of air in the tunnel was small, average of x directional velocity U_m was easy to be large by thermal fume buoyancy because of the gradient, and thermal fume velocity is larger than small gradient. Accompanied by this, evacuees near the fire point were surrounded by thick smoke due to be caught up and be unable to evacuate. In the case of longer than 1500 m, a total of mass of air in the tunnel was large and U_m was slow even if the buoyancy interacted similarly to L = 1000 m and a point of smoke velocity was smaller, therefore, smoke was difficult to catch up to the evacuees. That's why, NPRH increased between L = 1000 and 1500 m. On the other hand, in the case of g = 4 %, Fig. 25 shows that NPRH is the largest in L = 1500 m. Fig. 26 shows U_m with time in the case of g = 4 %. U_m in the case of L = 500 m started increasing the most rapidly, however, increased slowly after 240 seconds from fire starting and was constant at 480 seconds. U_m in the case of L = 1000 m started increasing from 300 seconds abruptly and became bigger than double of U_m in the case of L = 500 m at 600 seconds. U_m in the case of L = 1500 m was smaller than the case of L = 1000 m and thermal fume velocity also decreased, however, due to be larger than evacuating velocity, NPRH in the case of L = 1500 m increased because the evacuating distance was longer than L = 1000 m. On the other hand, in the case of L = 2000 m, a point of smoke velocity was smaller than the case of L = 1500 m, hence NPRH in the case of L = 2000 m was smaller than L = 1500 m. So that, it is considered that a danger in tunnel fire is not necessarily in proportion to tunnel length, depending on gradient, the danger doesn't reduce even in short tunnels.

For reference, Evacuees behavior maps in cases of (i) g = 0%, (ii) 1%, (iii) 2%, and (iv) 4% indicate in Figs. 27 to 31 each of L.

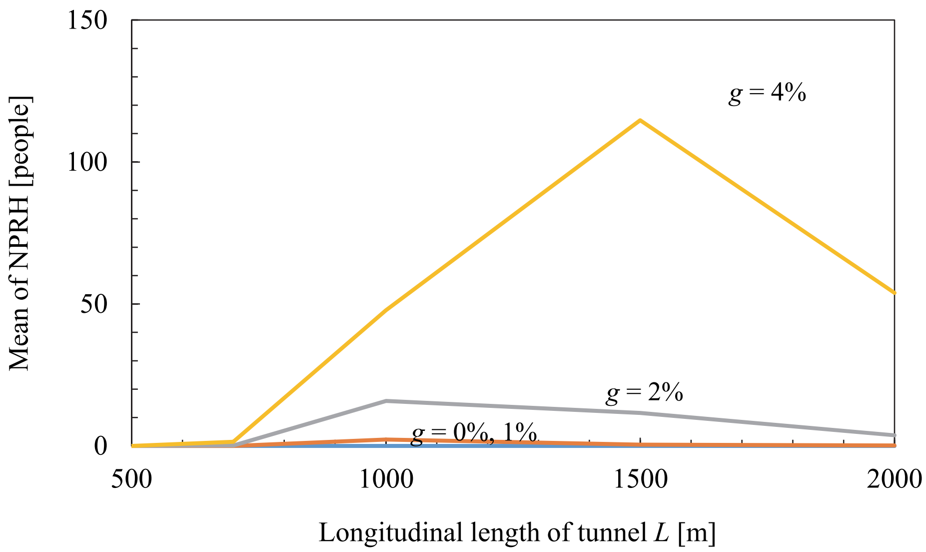


Fig. 25 Influence of tunnel longitudinal length and gradient

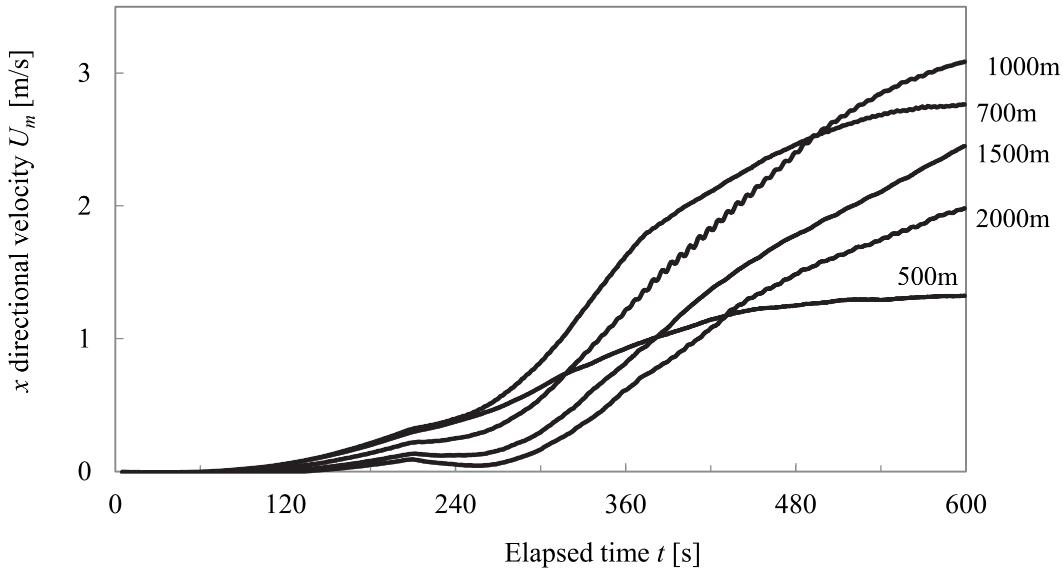
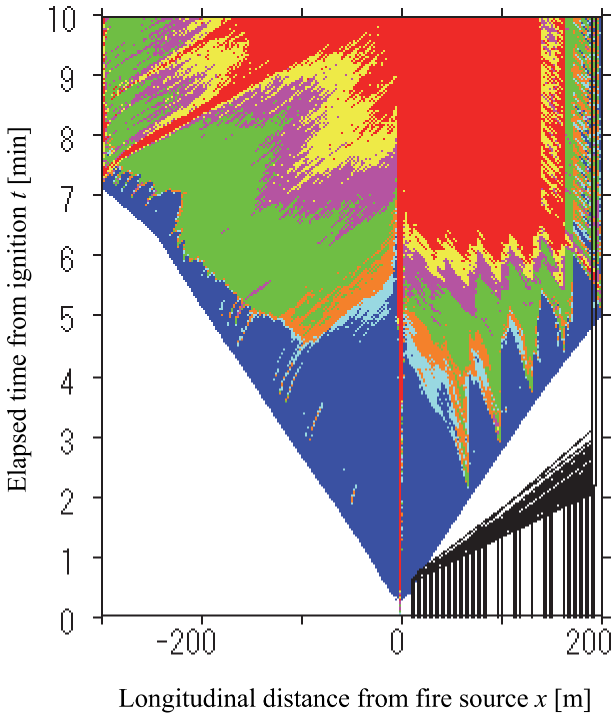
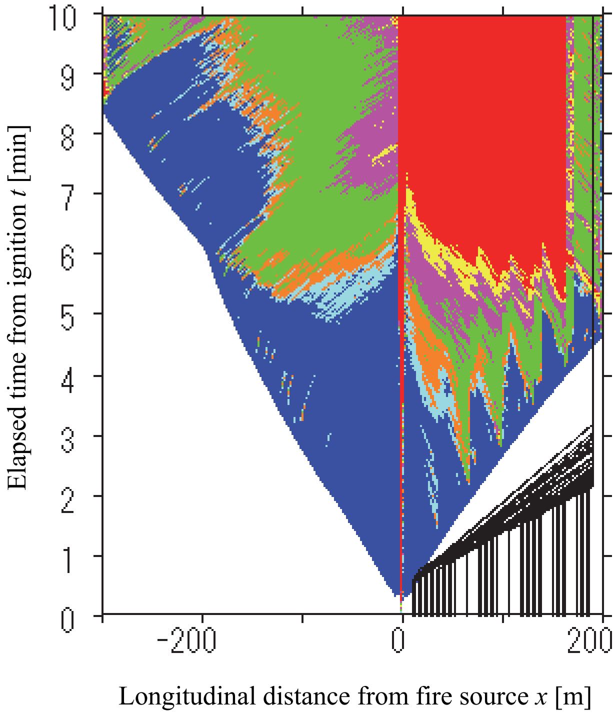


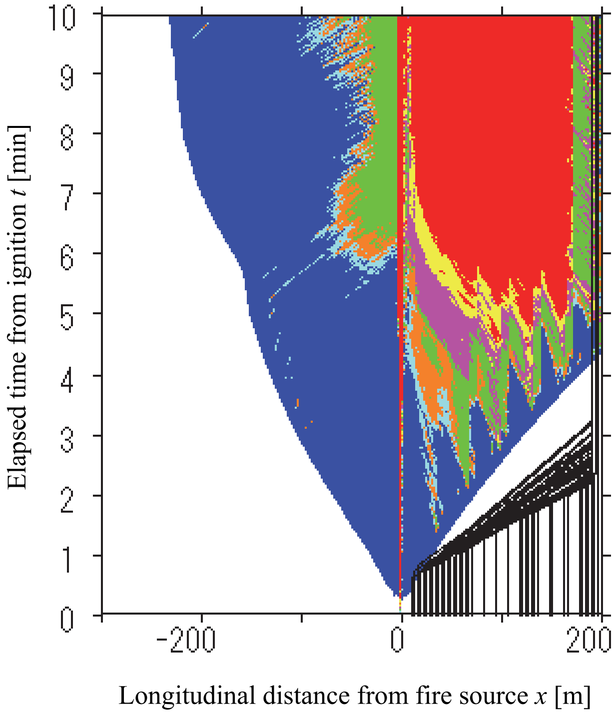
Fig. 26 Mean of longitudinal velocity U_m (g = 4 %, x = 50 m)



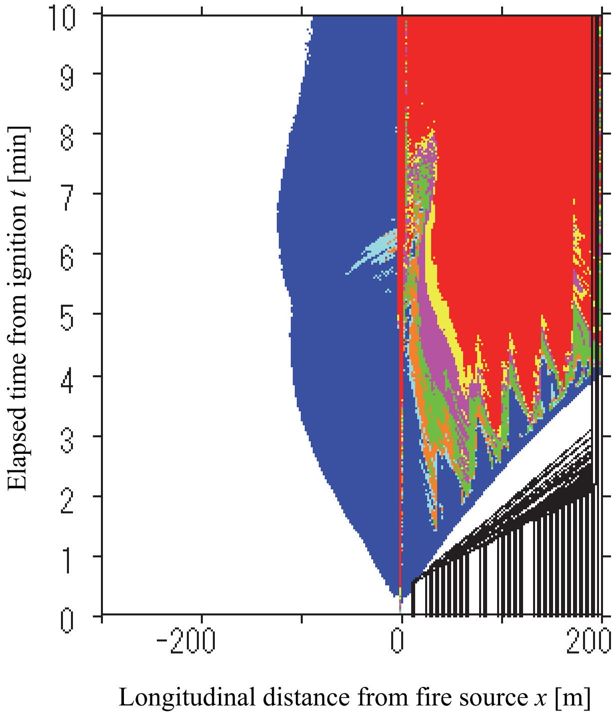
(i) g = 0 %


Elapsed time from ignition t [min]
0
1
2
3
4
5
6
7
8
9
10
-200
0
200
Longitudinal distance from fire source x [m]

(ii) $g = 1$ %

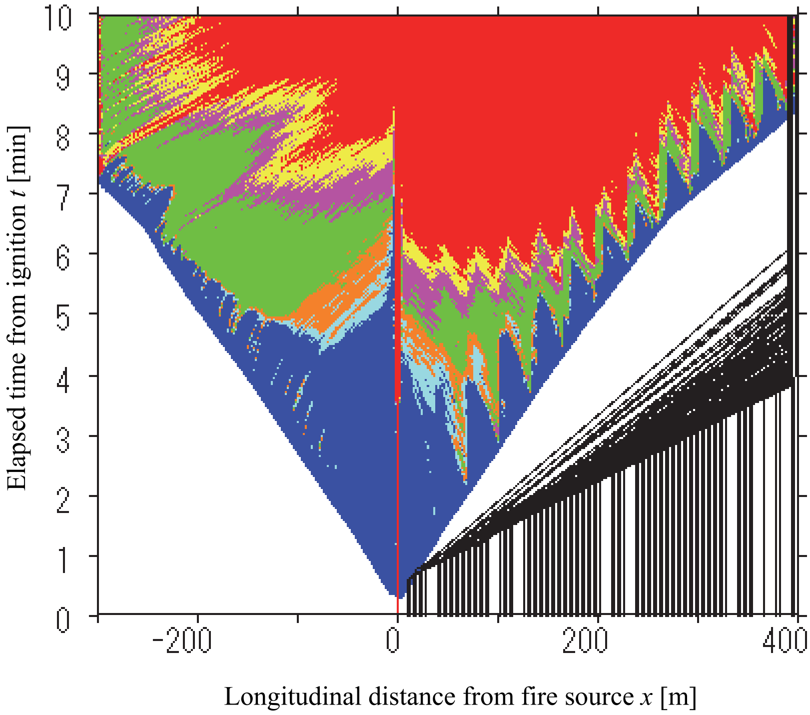

Elapsed time from ignition t [min]
0
1
2
3
4
5
6
7
8
9
10
-200
0
200
Longitudinal distance from fire source x [m]

(iii) $g = 2$ %

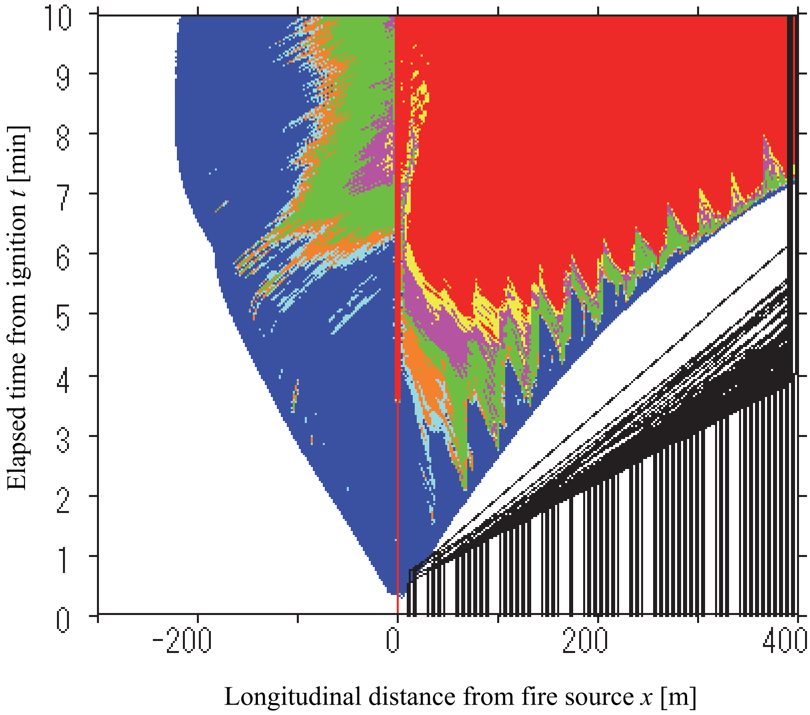


(iv) $g = 4$ %

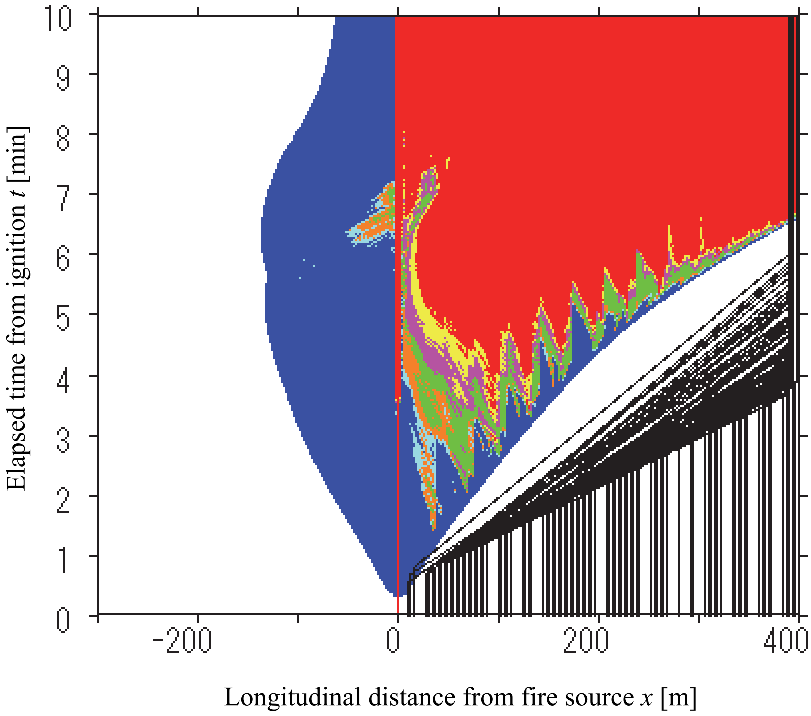
Fig. 27 Evacuees behavior map ($L = 500$ m)


Elapsed time from ignition t [min]
0
1
2
3
4
5
6
7
8
9
10
-200
0
200
400
Longitudinal distance from fire source x [m]

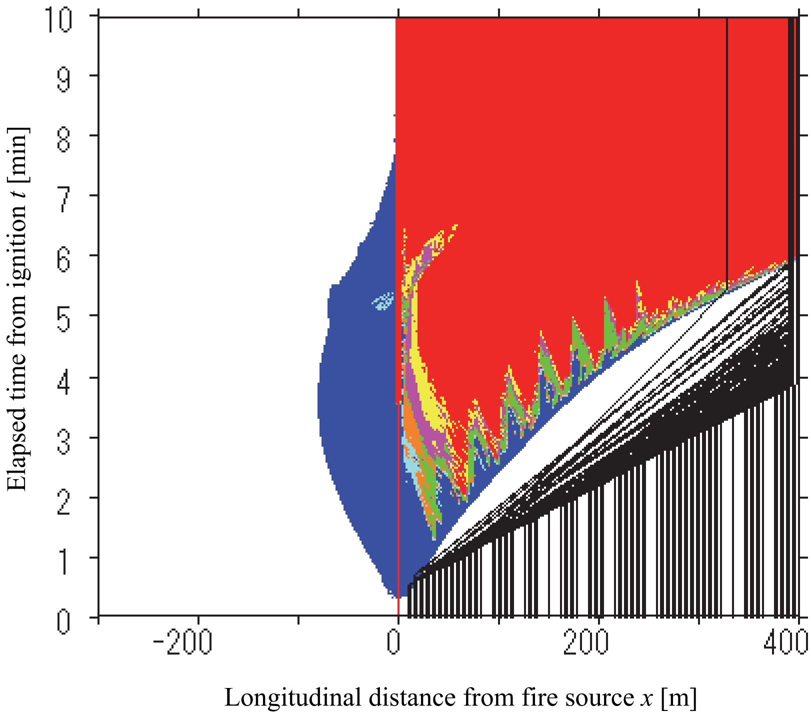
(i) g = 0 %


Elapsed time from ignition t [min]
0
1
2
3
4
5
6
7
8
9
10
-200
0
200
400
Longitudinal distance from fire source x [m]

(ii) g = 1 %

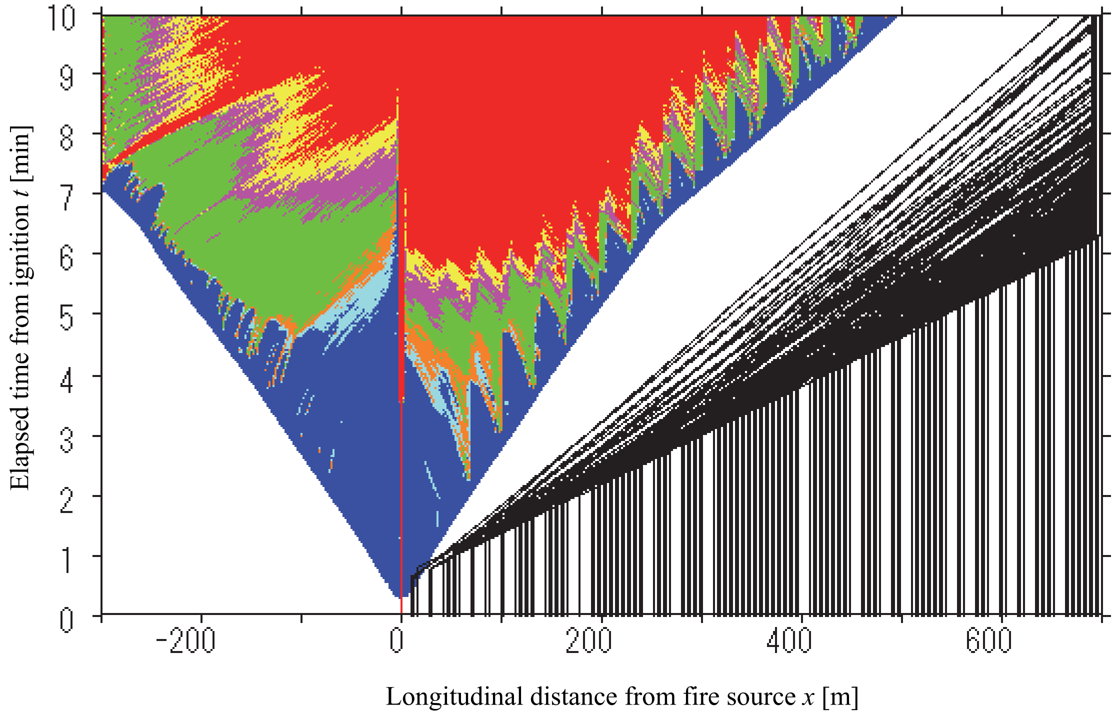


(iii) $g = 2$ %

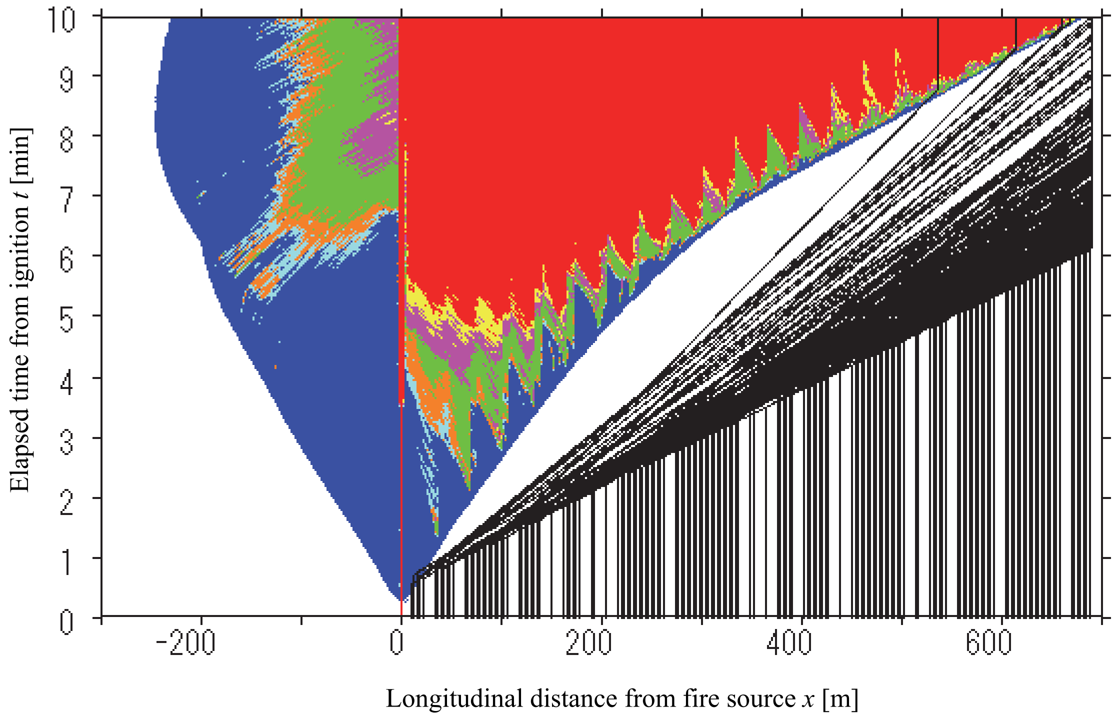


(iv) $g = 4$ %

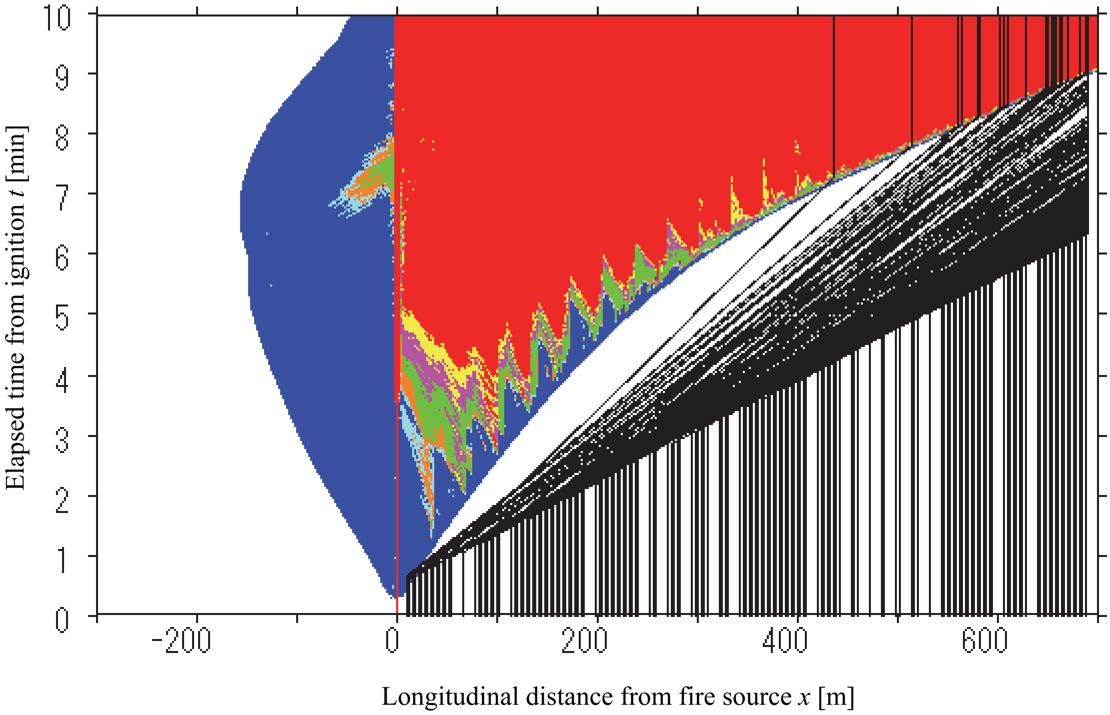
Fig. 28 Evacuees behavior map (L = 700 m)


10
9
8
7
6
5
4
3
2
1
0
Elapsed time from ignition t [min]
-200
0
200
400
600
Longitudinal distance from fire source x [m]

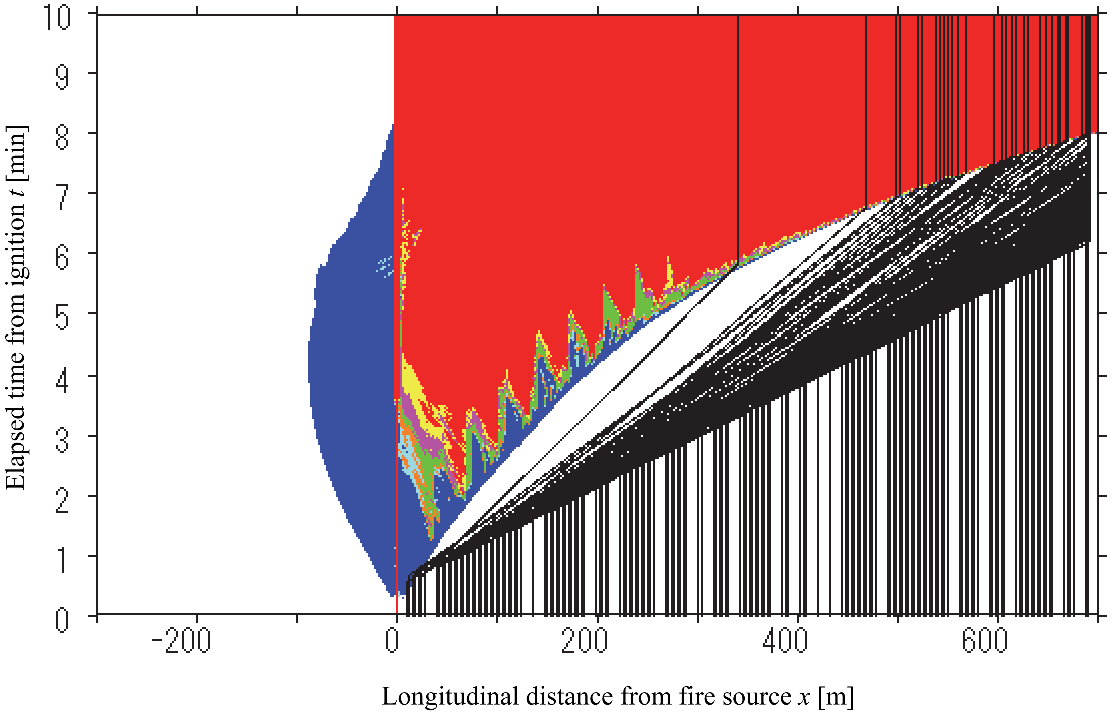
(i) $g = 0$ %


10
9
8
7
6
5
4
3
2
1
0
Elapsed time from ignition t [min]
-200
0
200
400
600
Longitudinal distance from fire source x [m]

(ii) $g = 1$ %

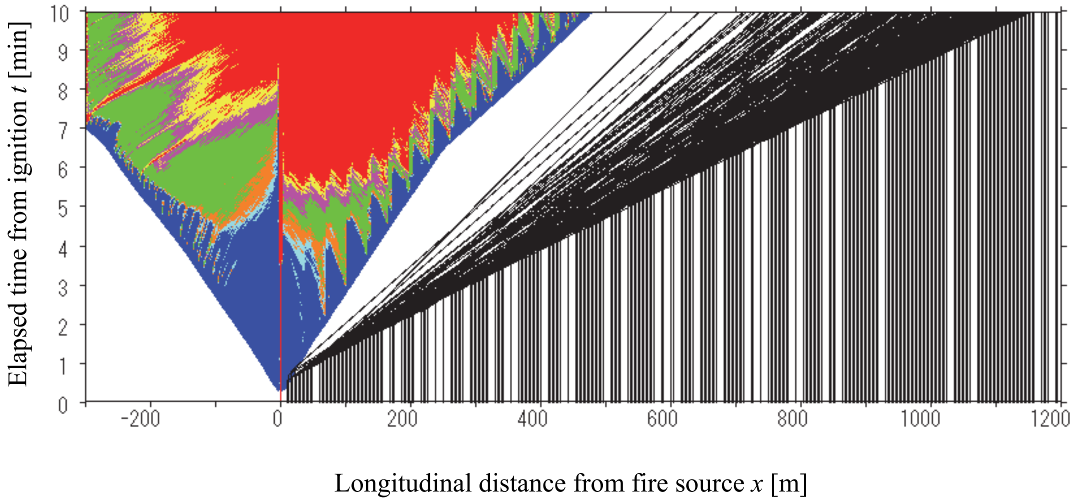


(iii) $g = 2$ %

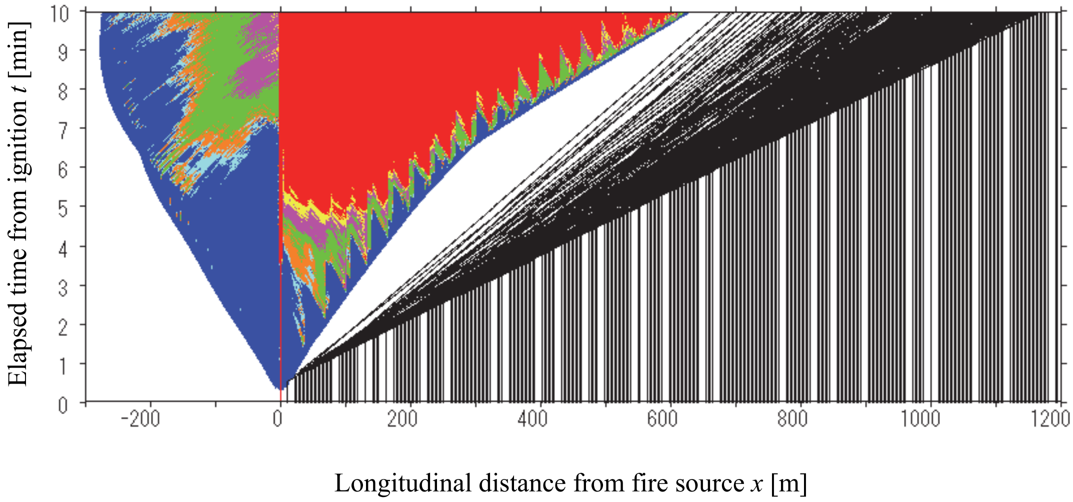


(iv) $g = 4$ %

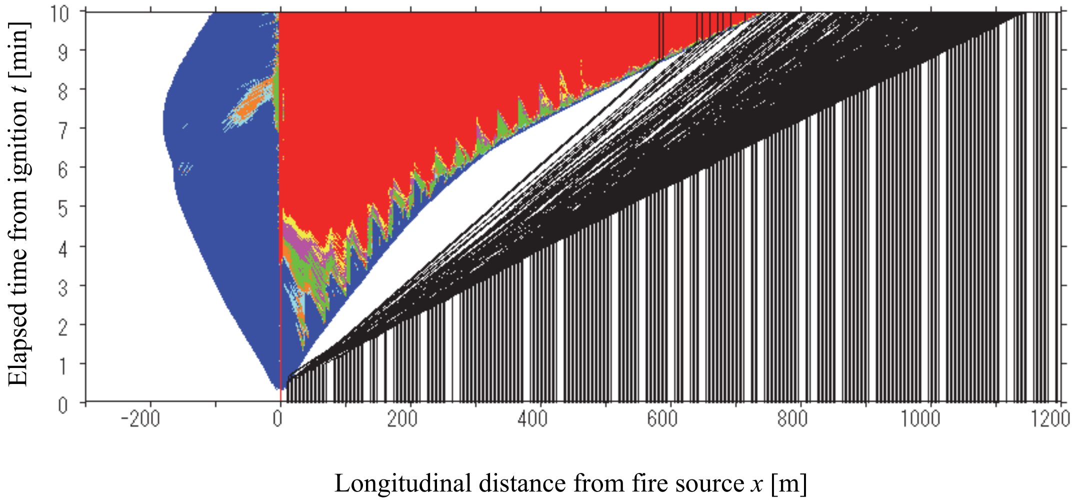
Fig. 29 Evacuees behavior map (L = 1000 m)


Elapsed time from ignition t [min]
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
600
800
1000
1200
Longitudinal distance from fire source x [m]

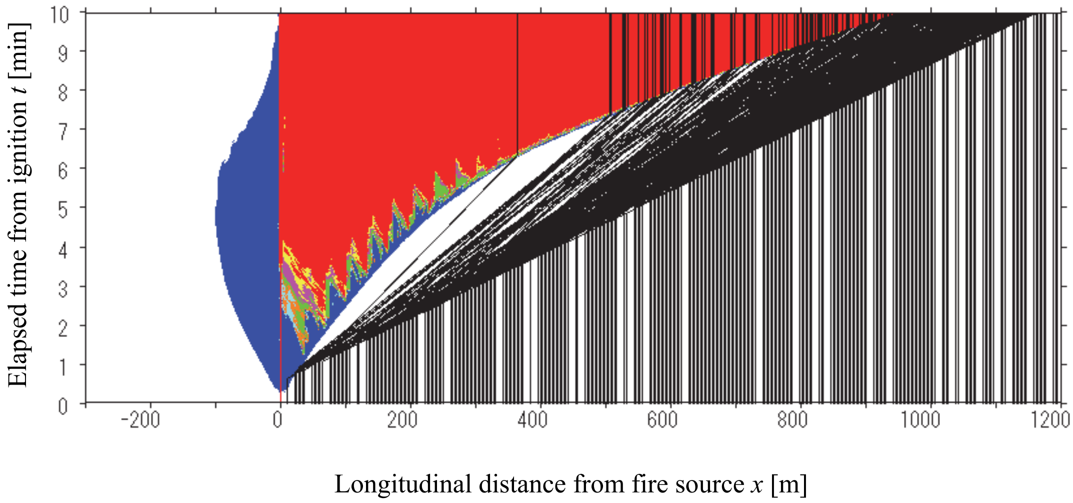
(i) $g = 0$ %


Elapsed time from ignition t [min]
10
9
8
7
6
5
4
3
2
1
0
-200
0
200
400
600
800
1000
1200
Longitudinal distance from fire source x [m]

(ii) $g = 1$ %

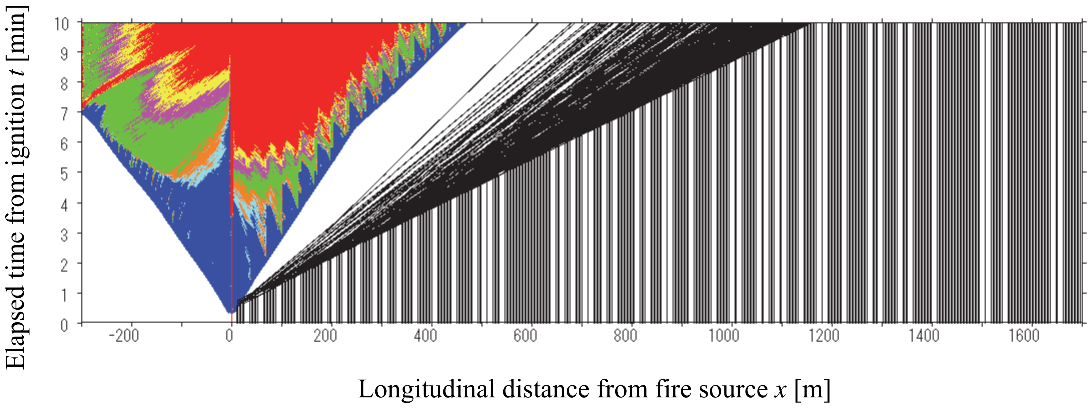


(iii) $g = 2$ %

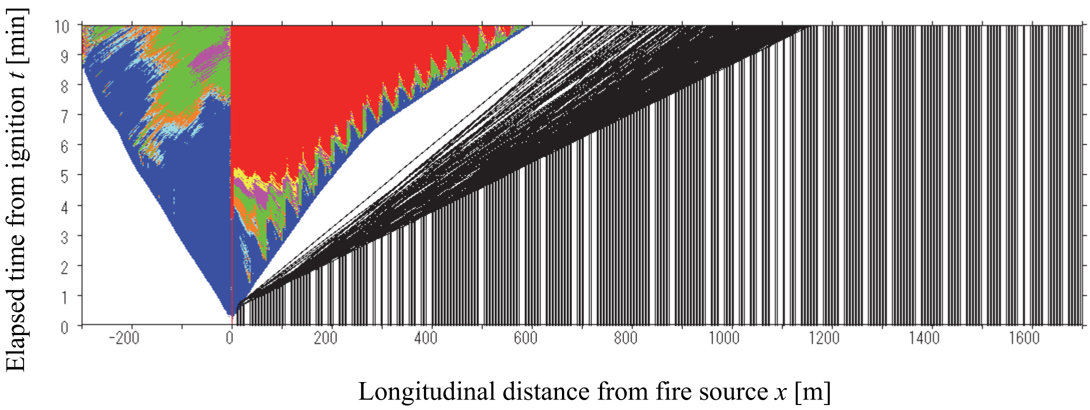


(iv) $g = 4$ %

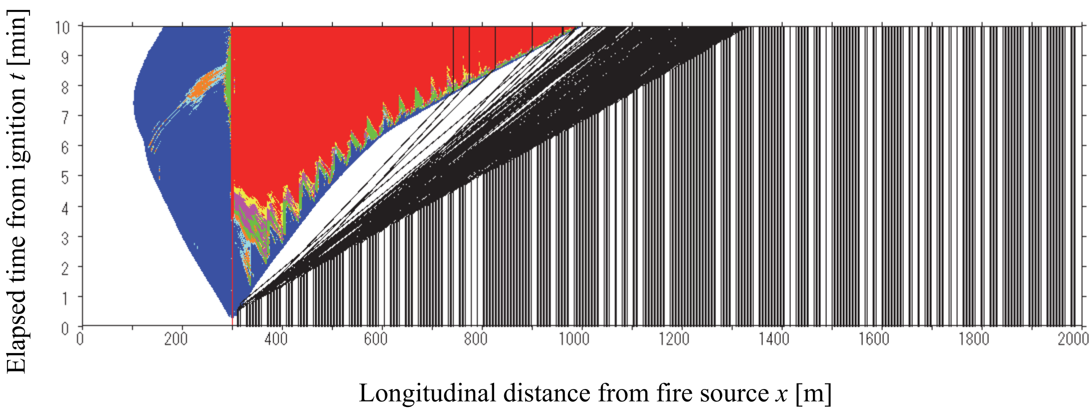
Fig. 30 Evacuees behavior map (L = 1500 m)



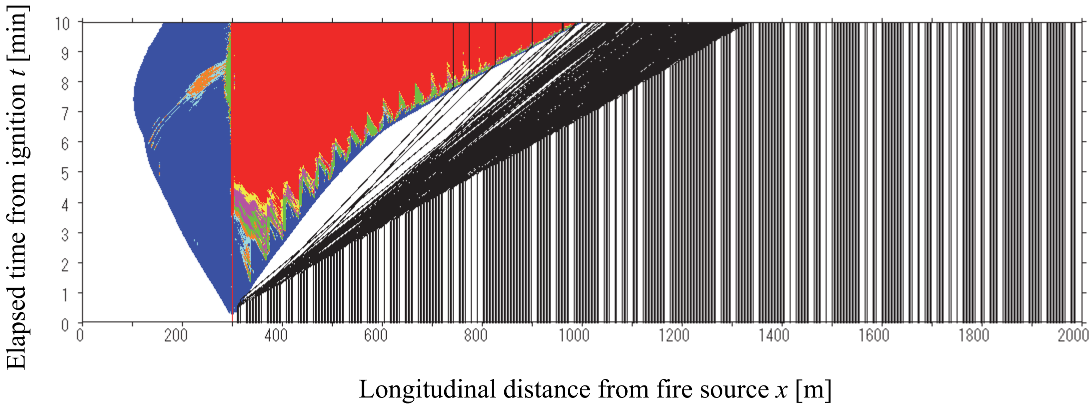
(i) $g = 0$ %



(ii) $g = 1$ %



(iii) $g = 2$ %



(iv) g = 4 %

Fig. 31 Evacuees behavior map (L = 2000 m)

5.3.2 Location of people surrounded by smoke

Fig. 32 indicates distribution of every 50 m location of NPRH in the tunnel in the case of g = 4 % and 90 seconds emergency announcement time from fire starting. Fig. 32 shows that NPRH increased longer than 500 m from the fire point rapidly. This is because a point of smoke velocity was larger than evacuees' velocity because of buoyancy of thermal fume as the last chapter.

Fig. 33 shows Evacuees Behavior map in the same case of Fig. 32 each of L. Fig. 33(iv) indicates that a point of smoke velocity was larger than evacuees' velocity longer than 500 m from the fire point and evacuees were caught up by the smoke and became PRH. Therefore almost evacuees can evacuate shorter than 500 m from the fire point.

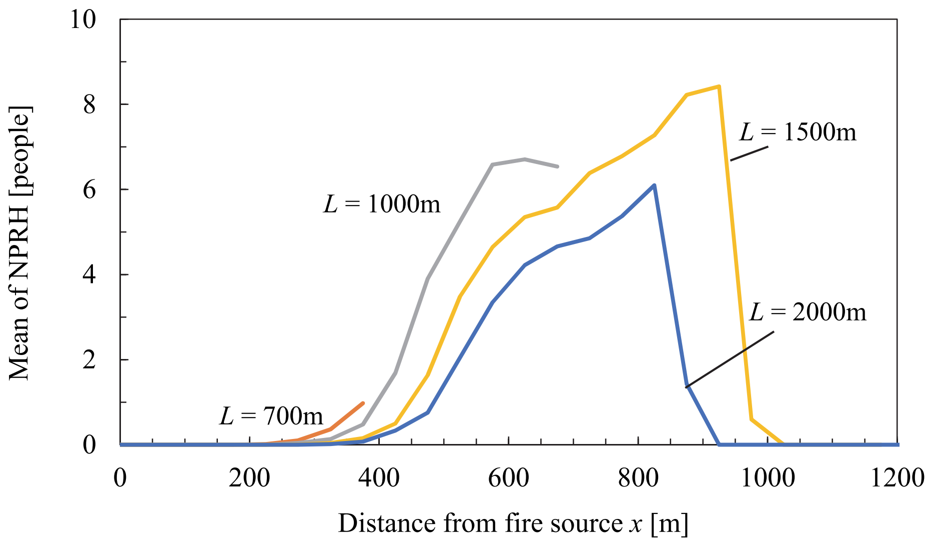
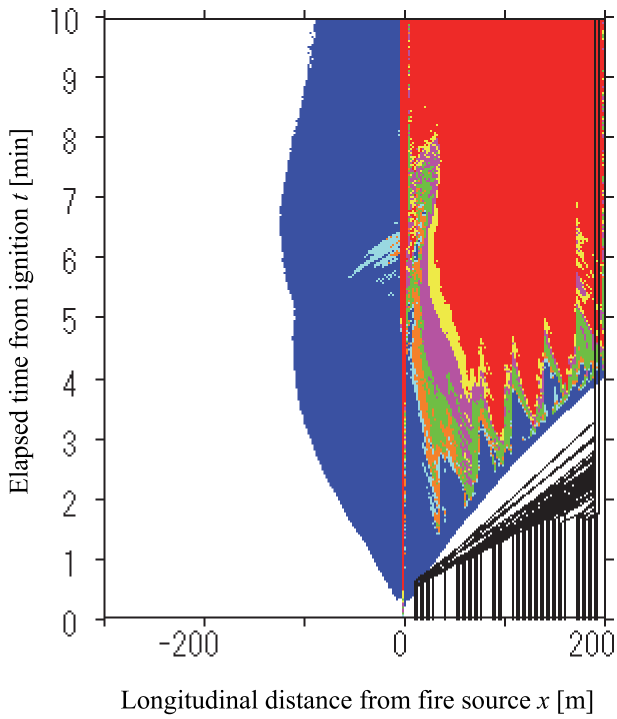
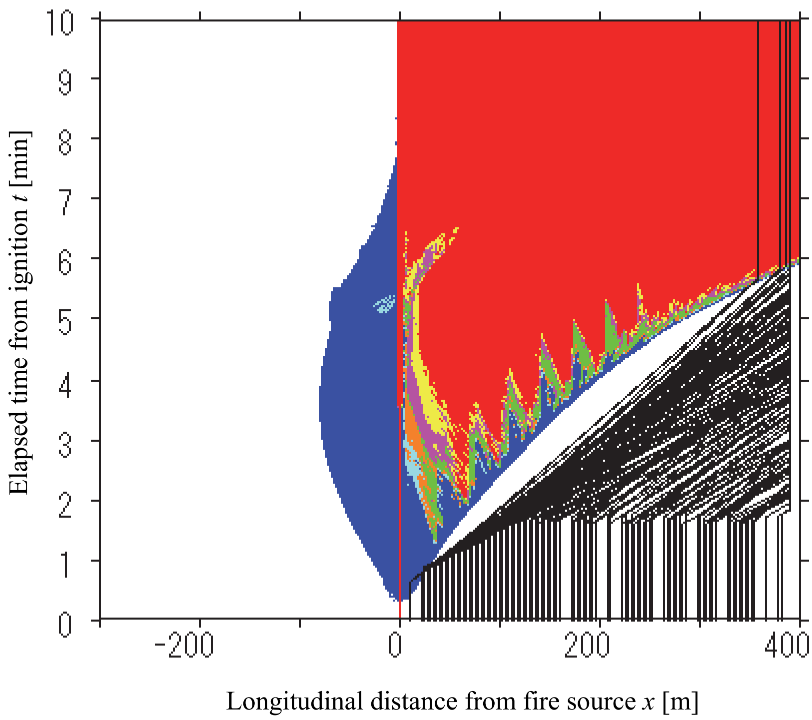


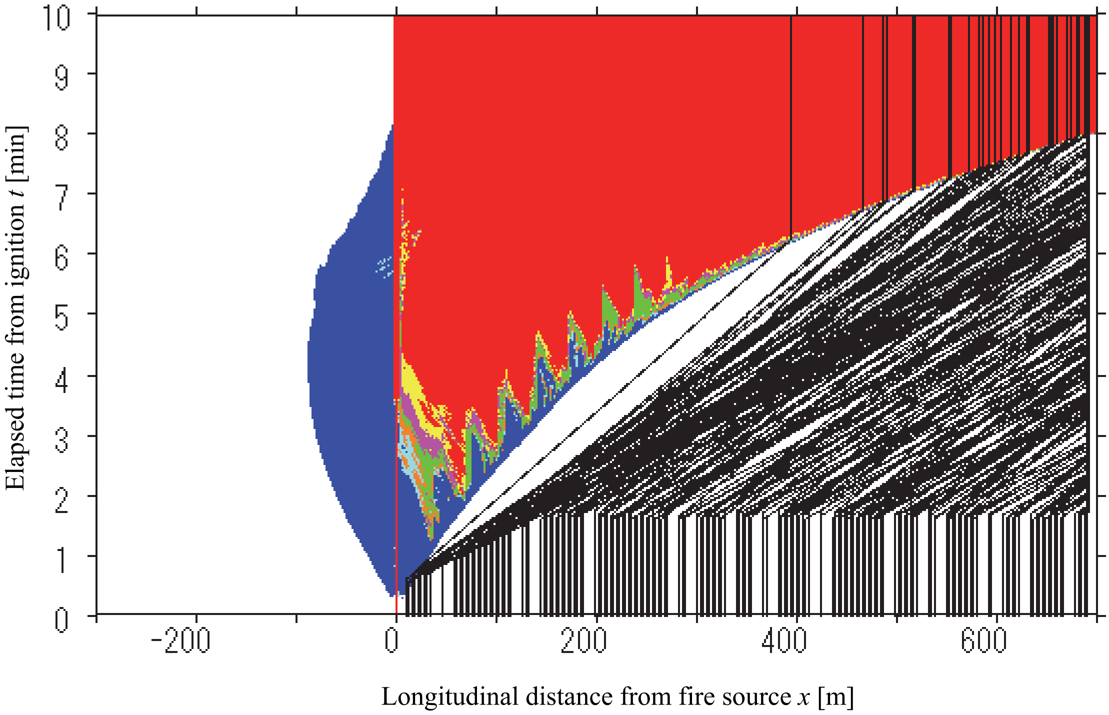
Fig. 32 Location of PRH (g = 4%, Emergency announcement time 90 s)



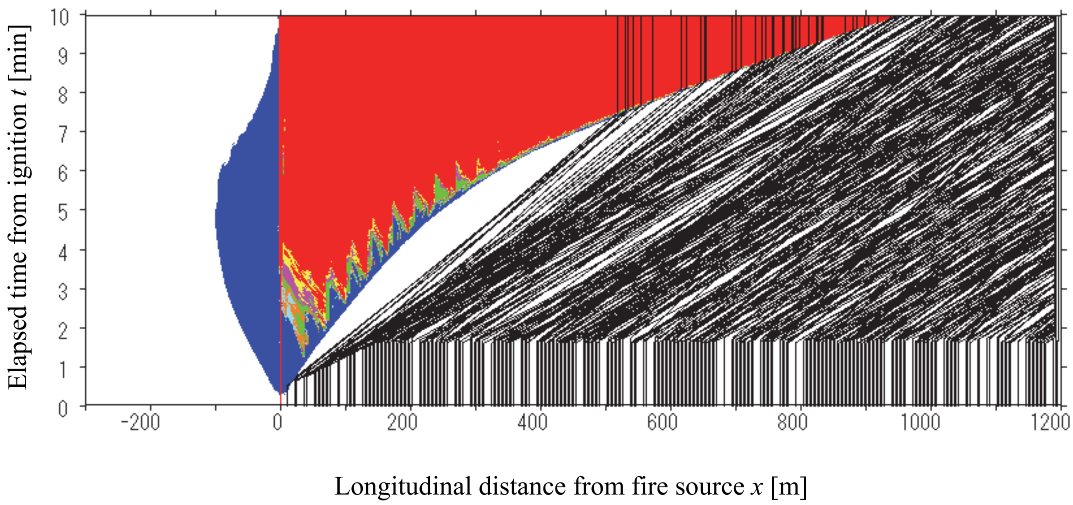
(i) L = 500 m



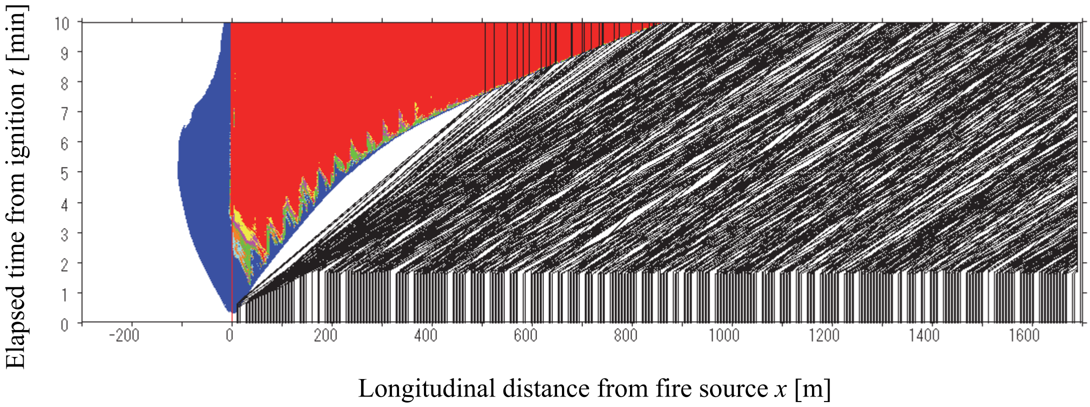
(ii) L = 700 m



(iii) L = 1000 m



(iv) L = 1500 m



(v) L = 2000 m

Fig. 33 Evacuees behavior map (g = 4%, Emergency announcement time 90 s)

5.4 Summary

In the present chapter, as application examples of suggesting assessment method, effect of emergency announcement, influence of the longitudinal gradient, and longitudinal length were clarified, so that the following results were obtained.

1. Depending on the gradient, even short tunnels have dangerous in a fire.
2. Evacuation walking speed is huge influence to NPRH, especially maximum of evacuation walking speed being large is effective to make communication to the users in tunnel fast, so that it is possibly considered that NPRH reduces. Hence, it was found that communication immediately to the users in tunnel was important.
3. It was found that emergency announcement is preferable in 60 s from ignition. In this case, it is considered that smoke tip propagating velocity becomes large influenced by buoyancy short tunnel of 700 m in length, so that emergency announcement effect becomes small.
4. There exists influence to tunnel fire safety by the start of heat release rate.
5. NPRH does not decreased even if reducing smoke generation volume.
6. NPRH is the largest in the range between L = 1000 and 1500 m. Because a total of mass of air in the tunnel was small, average of x directional velocity U_m was easy to be large by thermal fume buoyancy because of the gradient, and thermal fume velocity is larger than small gradient.
7. Increasing the gradient, NPRH increases rapidly in longer than L = 1000 m. So that, it is considered that a danger in tunnel fire is not necessarily in proportion to tunnel length, depending on gradient, the danger doesn't reduce even in short tunnels.
8. The velocity of smoke becomes large rapidly independently of tunnel length, and people can evacuate shorter than 500 m from the fire point.

6. CONCLUSIONS

In chapter 1, the present paper's motivation, the background in Japan and introduction are explained. A number of tunnels in Japanese expressway is as same as the total of the number in EU, it can be said that Japan is a tunnel country of the greatest in the world, more people use tunnel than other countries. Meanwhile, EU directives were announced officially in 2004, all highway tunnels longer than 500 m length must be investigated safety measurements [5], the strict standard has be applied comparing Japanese. Hence the higher and more reasonable measures are needed.

In chapter 2, considered characteristics of tunnel fires calculation code, assessment index, geometries and condition are determined. Main results are as follows;

1. Considering thermal flow in tunnel fires, in the present study, LES turbulence model (standard Smagorinsky model) 3-D CFD analysis (Fireles) is used. Fireles was developed in 1998 in Japan by one of authors, specialized tunnel fire, endothermic model to the ceiling and wall, which influenced dominantly to the thermal layers' behavior, considered since initial stage developing the simulation.
2. Factors preventing the evacuees in tunnel from evacuation in fires are considered temperature rising, toxic gas (generally CO) and smoke density around evacuees. However, tunnel internal volume is large, and the length is more than hundreds meter long, so that tunnel space is considerable to use smoke density appropriately. Also in Japan, smoke density is used as assess the evacuation environment because evacuees' visibility goes bad by smoke and then evacuees can’t evacuate anymore before evacuees dying, worsening of the visibility by smoke is governed the evacuation. In the present study, Concentration of smoke (*Cs*), which is a kind of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density.
3. Model tunnel was adopted a rectangular section, the total length of 700 meters, 5 meters height, 10 meters width, two-lane and one-way, which were not installed ventilation instrument and emergency announcement.
4. Fire scenario is determined by the past experiment [18].

In chapter 3, simplifying the smoke situation around evacuees, smoke environment levels (SE levels) are determined from *z* directional distribution of Cs_y (*x*, *z*), which can be obtained 2-D distribution averaging 3-D *Cs* density distribution by CFD analysis, as influence degrees which smoke hinder the evacuees' activities, at any *x* point on time *t*. Main results are as follows;

1. Considering tunnel height and evacuees situation, SE levels determined as an index of influence for evacuees by smoke height and *Cs* density.
2. Smoke Environment map (SE map) was developed contour diagram based on SE levels (colors of Table 1) and letting elapsed time from the ignition be the vertical axis and the tunnel length the horizontal axis. Thereby, behavior of thermal layer can be read from SE map.

In chapter 4, to develop the evacuation behavior model in tunnel fires, at first past studies treated evacuation inside buildings and huge disasters are investigated. Secondly, evacuation model in smoke of tunnel fires were developed. Main results are as follows;

1. Considering smoke behavior inside tunnels made a great impact on evacuees' behavior, smoke behavior consists complicated behavior in tunnels with gradient, natural ventilation, application of ventilation facilities, heat release rate scale, etc., moreover, evacuation under the smoke layer has to be supposed, hence evacuation behavior simulation using smoke behavior detailed analysis is necessary. In the present paper, using SE levels in chapter 3 by 3-D LES-CFD analysis in chapter 2, the evacuation behavior simulation considered smoke optical density is suggested. Evacuees' behavior does not influence to smoke behavior, so that evacuation behavior simulation in the present paper becomes 1-way coupling to CFD analysis of smoke behavior.
2. The present suggested evacuation behavior model is chasing each evacuees' behavior, and considering each evacuees' phenomenon occurred in evacuating. Tunnel spaces are extremely long comparing with wide length, but having around 10 m wide, so that tunnels are huge, enclosed and unique. Meanwhile, tunnel users existing concentratedly in a place are seldom, but are dotted with traffic jam sections. Therefore, when evacuees go through roadways where become evacuation passages in emergency situation, even if there are vehicles stopped, it can be considered that

evacuees can go through the side easily, influence of physical interference between evacuees is disregard, so that it is defined that evacuees can pass the others. Also evacuees can recognize the longitudinal direction of tunnel and to lose sight of the evacuation direction is not considered, so that evacuation behavior is treated one-dimensional behavior limited to longitudinal x direction.

3. The factors to recognize the necessity of evacuation are determined phenomena around evacuees, communication by other evacuees and information by the outside (emergency announcement).
4. Evacuation walking speeds is determined by situation of smoke around the evacuees, that is SE levels. Investigation of the prevention disaster of tunnel fires in Japan is also used based on Jin's results [17], so that SE level 4 (Cs = 0.4 m^{-1} at z = 1.5 m) is the situation when evacuees are surrounded by smoke and stop evacuation, evacuation walking speed v = 0 m/s.
5. Evacuation walking speed curves are determined by each references. Case 1 is determined by consideration that mean of evacuation walking speed 1.3 m/s is based on the reference [35], the minimum of evacuation walking speed is 1 m/s, which is generally adopted on tunnel fire safety, the evacuation walking speed range is from 0.9 m/s to 1.7 m/s. Case 2 is determined on the reference [36], mean of evacuation walking speed 1.33 m/s, fast walking speed 2 m/s. Cases 1 and 2 are based on the general walking speed measures. Case 3 is supposed the hurry situation, mean of walking speed 1.5 m/s during morning commuting hours on The Architectural Institute of Japan, Handbook of Environmental Design [37], and used the same idea as case 1. More serious situation is in case 4, Bore [38] measured evacuation walking speed, whom explained that there was in a danger of explosion and they must evacuate immediately etc., used the actual tunnel, as a consequence, mean of speed 2.3 m/s, maximum of speed 3.1 m/s were obtained.
6. Drawn the black solid lines of changes in each evacuees' location on smoke environment map, to indicate smoke behavior and evacuees activities can show in the same time, which is defined as evacuees behavior map. Investigating evacuees behavior map, smoke behavior and evacuees' activities with every moment can be seen perfectly in evacuees behavior map.

7. In an assessment time (10 min in the present study) from ignition, evacuees who are surrounded by smoke and cannot evacuate safely, are defined as sufferers, a Number of People Requiring Help (NPRH) are used as indicator of assessment for tunnel fire safety in the present paper. In the present paper as follows are used as mean of value of 1000 times.

In chapter 5, as application examples of suggesting assessment method, effect of emergency announcement, influence of the longitudinal gradient, and longitudinal length were clarified, so that the following results were obtained.

1. Depending on the gradient, even short tunnels have dangerous in a fire.
2. Evacuation walking speed is huge influence to NPRH, especially maximum of evacuation walking speed being large is effective to make communication to the users in tunnel fast, so that it is possibly considered that NPRH reduces. Hence, it was found that communication immediately to the users in tunnel was important.
3. It was found that emergency announcement is preferable in 60 s from ignition. In this case, it is considered that smoke tip propagating velocity becomes large influenced by buoyancy short tunnel of 700 m in length, so that emergency announcement effect becomes small.
4. There exists influence to tunnel fire safety by the start of heat release rate.
5. NPRH does not decreased even if reducing smoke generation volume.
6. NPRH is the largest in the range between L = 1000 and 1500 m. Because a total of mass of air in the tunnel was small, average of x directional velocity U_m was easy to be large by thermal fume buoyancy because of the gradient, and thermal fume velocity is larger than small gradient.
7. Increasing the gradient, NPRH increases rapidly in longer than L = 1000 m. So that, it is considered that a danger in tunnel fire is not necessarily in proportion to tunnel length, depending on gradient, the danger doesn't reduce even in short tunnels.
8. The velocity of smoke becomes large rapidly independently of tunnel length, and people can evacuate shorter than 500 m from the fire point.

REFERENCE

[1] Japan Institute of Construction Engineering, Suggestion “For the purpose of road tunnels safety improvement”, 2007. (in Japanese)

[2] Bailey, C.: Case Studies: Historical Fires: Mount Blanc Tunnel Fire, Italy/France, http://www.mace.manchester.ac.uk/project/research/structures/strucfire/CaseStudy/HitoricFires/InfrastructuralFires/mont.htm.

[3] Leitner, A.: The fire catastrophe in the Tauern Tunnel: experience and conclusions for the Austrian guidelines, Tunneling and Underground Space Technology, Vol. 16, pp. 217-223, 2001.

[4] Japan Road Association, Installation Criteria and Explanation of Road Tunnel Emergency Facilities, 2001. (in Japanese)

[5] The European Parliament and the Council of the European Union: Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European road network, 2004.

[6] Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communication: Firefighting white paper Heisei 14th version, Printing Bureau of the Ministry of Finance, 2002. (in Japanese)

[7] Fire and Disaster Management Agency of the Ministry of Internal Affairs an d Communication: Firefighting white paper Heisei 24th version, http://www.fdma.go.jp/html/hakusho/h24/h24/html/2-1-9c-1.html, 2012. (in Japanese)

[8] Fire and Disaster Management Agency of the Ministry of Internal Affairs an d Communication: Firefighting white paper Heisei 25th version, http://www.fdma.go.jp/html/hakusho/h25/h25/pdf/part1_section8.pdf, 2013. (in Japanese)

[9] Kawabata, N., Wang, Q., Yagi, H. and Kawakita, M.: Study of Ventilating Operation during Fire Accident in Road Tunnels with Large Cross Section, Proceedings of the Fourth KSME-JSME Fluid Engineering Conference, Pusan, pp. 53-56, 1998.

[10] Wang, Q., Kawabata N., and Ishikawa, T., Evaluation of Critical Velocity Employed to Prevent the Backlayering of Thermal Fume during Tunnel Fires, Proceedings International Conference on Applied Computational Fluid Dynamics, Beijing, 2000, pp.404-411.

[11] Kawabata, N., Kunikane, Y., Yamamoto, N., Takekuni, K., and Shimoda, A.: Numerical Simulation of Smoke Descent in a Tunnel Fire Accident, Tunnel Management International, Vol. 6, No. 4, pp. 45-52, 2003.

[12] Kunikane, Y., Kawabata, N., Takekuni K., and Shimoda, A., Heat Release Rate in a Large Cross Section Tunnel, Tunnel Management International, 6, 3, pp.22-29, 2003.

[13] Kikumoto, T., Kawabata, N., Maruyama, D., and Yamada, M., Characteristic of Plume Behaviour in a Small Section Road Tunnel only for Passenger Cars (A Study by Numerical Simulation), Proceedings of JSCE, Ser. F, Vol. 63, No. 4, pp. 448-459, 2007. (in Japanese)

[14] Kohl, B., Botschek, K. and Hörhan, R.: Austrian Risk Analysis for Road Tunnels: Development of a new Method for the Risk Assessment of Road Tunnels, 3rd International Conference “Tunnel Safety and Ventilation” 2006, Graz, pp. 204-211, 2006.

[15] NIST: Fire Dynamics Simulator and Smokeview (FDS-SMV), Official Website, Hosted at the National Institute of Standards and Technology (NIST), http://fds-smv.googlecode.com/svn/trunk/FDS/trunk/Manuals/All_PDF_Files/FDS_User_Guide.pdf.

[16] Sekizawa, A., Ebihara, M., Kadokura, H., Suematsu T., and Takahashi, W., Examination of Evacuation Safety in the Underground Railroad Station in consideration of Smoke Effect, the Architectural Institute of Japan Conference Abstracts, 2005, pp. 229-230. (in Japanese)

[17] Dobashi, M., Imai, T., Yanagi, H., Mizuno, A. and BHR Group: Numerical simulation of the emergency tunnel ventilation for a tunnel with longitudinal and transverse systems combined, 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Vol. 43, pp. 581-595, 2000.

[18] Ejiri, Y. and Kawabata, N., Smoke Generation of Fire Tests of Real Scale Tunnel, The Japan Society of Mechanical Engineering Fluids Engineering Division Proceedings, 2005, pp.181-184. (in Japanese)

[19] Ingason, H.: Heat release rate measurements in tunnel fires, Proc. Int. Conf. Fires in Tunnels, Sweden, pp. 86-103, 1994.

[20] Togawa, K., Calculation of Evacuation Mass Flow, Journal of architecture and building science, Vol. 69, No. 809, pp. 15-19, 1954.

[21] Kiyono, J., Miura, F., and Takimoto, K., Simulation of Emergency Evacuation Behavior during Disaster by using Distinct Element Method, Proceedings of JSCE, No. 537/I-35, pp. 233-244, 1996. (in Japanese)

[22] Kiyono, J., Toki, K., Inukai, N., and Takeuchi, T., Evaluation of Safety of Evacuation Behavior from an Underground Space during an Earthquake, Proceedings of JSCE, No. 689/I-57, pp. 31-43, 2001. (in Japanese)

[23] Takimoto, K., Miura, F., and Kiyono, J., Simulation of Evacuation Behavior in a Disaster and its Interaction with Guide's Instructions, Proceedings of JSCE, No. 537/I-35, pp. 257-266, 1996. (in Japanese)

[24] Yokoyama, H., Meguro, K., and Katayama, T., Application of Potential Model for the Analysis of Evacuation Behavior, Proceedings of JSCE, No. 513/I-31, pp. 225-232, 1995. (in Japanese)

[25] Mizuno, M., Tsuburaya, S., Yamada, S., Tanaka, T., Morita, M., and Wakamatsu, T., Development of the Dynamic Simulation Program for Evaluation of Evacuation Safety in the Building Fire: Part 2 Outline of the evacuation behavior model Summaries of technical papers of Annual Meeting Architectural Institute of Japan. A-2, Fire safety, off-shore engineering and architecture, information systems technology, pp. 217-218, 2005. (in Japanese)

[26] Nishino, T., Tsuburaya, S., Himoto, K., and Tanaka, T., Study on the Estimation of the Evacuation Behaviors of Tokyo City Residents in the Kanto Earthquake Fire: Development of a Potential-based Evacuation Model in Post-Earthquake fire, Journal of environmental engineering, 74(636), pp. 105-114, 2009.

[27] Ohkami, T., Asayama, Y., and Koyama, S., Evacuation Behavior Simulation of a Tunnel Fire Disaster considering the Influence of Smoke, Transactions of the Japan Society for Computational Methods in Engineering, Vol. 8, pp.1-6, 2008. (in Japanese)

[28] Thompson, Peter A. and Marchant, Eric W., Testing and Application of the Computer Model ‘SIMULEX’, Fire Safety Journal, 24,1995, pp.149-166.

[29] Gwynne, S., Galea, E. R., Lawrence, P. J. and Filippidis, L., Modelling occupant interaction with fire conditions using the buildingEXODUS evacuation model, Fire Safety Journal, 36, 2001, pp.327-357.

[30] Wu, G., Chien, S. and Huang, Y., Modelling the occupant evacuation of the mass

rapid transit station using the control volume model, Building and Environment, 45, 2010, pp. 2280-2288.

[31] Tanimoto, J., Hagishima A. and Tanaka, Y., Study of bottleneck effect at an emergency evacuation exit using cellular automata model, mean field approximation analysis, and game theory, Physica A, 389, 2010, pp.5611-5618.

[32] Japan Association for Fire Science and Engineering, Fire Manual Third Edition, p. 389, p. 1354, Kyoritsu Shuppan Co., Ltd., 1997. (in Japanese)

[33] Nilsson, D., Johansson, M. and Frantzich, H.: Evacuation experiment in a road tunnel: A study of human behaviour and technical installations, Fire Safety Journal, pp. 458-468, 2009.

[34] Jin, T., Visibility of Signs Through Fire Smoke (I), *Transactions of the Architectural Institute of Japan*, No. 182, 1971, pp.21-32. (in Japanese)

[35] Japan Association for Fire Science and Engineering, Fire Manual Third Edition, p. 551, Kyoritsu Shuppan Co., Ltd., 1997. (in Japanese)

[36] Murosaki, Y., Modern Architecture - Building Disaster Prevention and Safety -, p. 36, Kajima Institute Publishing Co., Ltd., 1993.(in Japanese)

[37] The Architectural Institute of Japan, Handbook of Environmental Design, Maruzen, Japan, 2003, p. 59 and p.142. (in Japanese)

[38] Boer, L. C.: Behaviour by motorists on evacuation of a tunnel, TNO Report, TM-02-C034, p. 23, 2002.

[39] Ministry of Land, Infrastructure, Transport and Tourism, Committee of Road Contract Evacuation Technique Examination Part 1, http://www.mlit.go.jp/road/ir/iinkai/1pdf/s1-54.pdf. (in Japanese)

[40] Tsukada, Y., Kiriyama, T., Hokuhara, H., and Hayama, K., Study on new design method about traffic capacity, Technical Note of National Institute for Land and Infrastructure Management No. 317, 2006. (in Japanese)

REFERENCE

Publication

1. Journal Paper

清家美帆，川端信義，長谷川雅人
煙流動 CFD を用いた避難行動シミュレーションによる道路トンネル火災安全性の評価方法
土木学会論文集 F2（地下空間研究），Vol. 70，No. 1，pp. 1-12，2014 年 3 月.

Miho Seike, Nobuyoshi Kawabata, Masato Hasegawa
Assessment method for road tunnel fire safety by evacuation simulation in smoke's behavior from CFD analysis
Journal of Japan Society of Civil Engineers, Ser., F2 (Underground Space Research), 70(1), pp. 1-12, March 2014. (in Japanese)

2. International Conference

(1) Miho Seike, Nobuyoshi Kawabata, Masato Hasegawa
Study About Assessment of Fire Safety in a Road Tunnel by Evacuee's Behavior based on Smoke Behavior by 3-D CFD Analysis, Advanced Research Workshop Evacuation and Human Behavior in Emergency Situations, pp. 111-125, October 2011. (Referred)

(2) Miho Seike, Nobuyoshi Kawabata, Masato Hasegawa
Simulation of evacuation using CFD analysis of fire accident in a road tunnel
The 2nd Japan/Taiwan/Korea Joint Seminar for Disaster Prevention Measures of Long Tunnel by Kanazawa Univ., Taiwan Central Police Univ. and Hoseo Univ., pp. 1-10, Kanazawa, Japan, November 2010. (Non-referred)

(3) Miho Seike, Nobuyoshi Kawabata, Masato Hasegawa
Influence of Tunnel Length Regarding Evacuation in a Fire Accident in Road Tunnels
The 4th Korea/Japan/Taiwan Joint Seminar for Disaster Prevention Measures of Long Tunnel, pp. 181-183, Seoul, Korea, November 2012. (Poster session, non-referred)

3. National Conference

(1) 清家美帆，川端信義
CFD を用いた道路トンネル火災の人的被害評価に関する研究
平成 22 年度日本火災学会研究発表会概要集，pp. 144-145，北海道，2010 年 5 月.

(2) 清家美帆，川端信義，長谷川雅人
道路トンネル火災時において発熱速度・発煙速度の経時変化が避難者に与える影響
安全工学シンポジウム 2010 講演予稿集，pp. 418-421，東京，2010 年 7 月.

(3) 清家美帆，川端信義
CFD 解析と避難シミュレーションによる道路トンネル火災の評価
熱工学コンファレンス講演論文集，pp. 103-104，長岡，2010 年 10 月.

(4) 清家美帆，川端信義，長谷川雅人
道路トンネル火災時の避難に対する延長長さによる影響
平成 23 年度日本火災学会研究発表会概要集，pp. 392-393，東京，2011 年 5 月.

Acknowledgement

I would like to express my sincere gratitude to my chief advisor, Prof. Kawabata for providing me the present precious research theme as a doctoral course student in his laboratory. Thank you very much. Prof. Kawabata supported to me very warmly when it was hard time for me mentally and physically about troubles of experiments and journaling up the papers. Additionally, Prof. Kawabata taught to me strictly but warmly who was crude as a researcher, and advised many things. Thank you very much.

I would like to express my deepest thanks to Prof. Hasegawa advised me about English and details when I had to submit the 2nd paper in the journal in the deadline approaching and achievement. I am very appreciating the members of my laboratory and Tunnel Fire Safety Research group.

Almost all school mates decided their jobs, there were many anxieties and vacillate of the road to go. In the situation, it was not long before, my internship in SFPE Taiwan chapter was decided by JST Young Researchers Training Program for Promoting Innovation DC course, when I entered doctoral course, the then President Prof. Chien, who is professor in Central Police University, told me strictly but warmly, "This is your way, you must pioneer your way by yourself." This word changes my attitude to research extremely, and helps me many times when I saw the high wall. Here was for me to be on my autonomy mark as a researcher. Thank you very much. Also, the present President, Prof. Shen, who is professor in Central Police University, supported me very kindly when it was tough time for me in Taiwan. Thank you very much.

Finally, I deeply appreciate to my father and my mother, cheered up "On your way" when I decided to go to the doctoral course and supported in 3 years without saying anything. Honestly in the beginning, I think you worried a lot and you saw to me being unsteady. I went a long way round, but I seem to be able to walk with steady steps from now. Thank you very much for raising me up until now.

January 2015 SEIKE Miho

Acknowledgement