Study on Quantitative Assessment of Road Tunnel Fire Safety

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Abstract

The present paper proposed quantitative assessment method for road tunnel fire safety by numerical simulation of evacuation in smoke. To evaluate the influence of smoke on evacuees, Smoke Environment Level (SE level) has been defined as a function of time and longitudinal location, by simplifying smoke distribution derived from 3-D CFD analysis and then weighting it with visibility. By mapping SE levels on time-distance plane, smoke's behavior in tunnel fire can be concisely expressed. In the developed 1-D evacuation simulation method using SE levels each evacuee recognized the necessity of evacuation through smoke's behavior, other evacuees' behavior or emergency announcement. The number of people who were surrounded by thick smoke in 10 minutes was used as evaluation index for tunnel fire safety. The present method has been tested in the cases of various longitudinal gradients and evacuees' moving speed. As application examples of suggesting assessment method, effect of emergency announcement, influence of the longitudinal gradient, and longitudinal length were clarified

1. Introduction

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.

2. Smoke Behavior Simulation

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].

3. SE level

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 map

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.

5. Calculation Example

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.

平成２７年　１月３０日

学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

Study on quantitative assessment of road tunnel fire safety

自動車トンネル火災安全性の定量的評価に関する研究

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３．審査結果の要旨（600～650 字）

当該学位論文に関し，平成 27 年 1 月 30 日に第 1 回学位論文審査委員会を開催し，提出された学位論文および関連資料について検討を加え，同日の口頭発表後，第 2 回審査委員会を開催し，協議の結果以下の通り判定した．

本論文は、道路トンネルの火災安全性について CFD と避難シミュレーションを連立した方法による定量的な評価指標について提案している。まず、CFD と避難シミュレーションの連立のため、トンネル火災時に発生する煙が避難者に及ぼす影響を 7 段階の危険度として定義している。この危険度の時間的な変化を線図として表すことにより、煙挙動の成層状態や拡散状態などの性状や拡がる範囲を 1 枚の図によって簡潔に表されることを示している。さらに、トンネル空間の細長い大空間という特徴を踏まえて、避難者行動の一次元シミュレーションを提案し、避難開始モデルおよび避難時の歩行速度モデルを提案している。この CFD と連立した避難シミュレーションにより火災発生から 10 分経過時に煙に暴露されている避難者を要救助者と定義し、その人数（NPRH）によってトンネル安全性の評価とすることを提案している。本方法の適用例として 700m の短いトンネルを用い、縦断勾配の増加に伴って急激に危険性が増加することを明らかにしている。

以上により本論文によって提案された道路トンネルの火災安全性の評価方法は、今後のリスク解析の導入および合理的なトンネル非常用設備の設計を可能にし、火災安全性向上に大いに貢献しうるものであり、工学的な寄与が大きく，博士（工学）の学位に値するものと判定した．

４．審査結果　(1) 判　　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（　工学　）