APPLICABILITY OF WATER SCREEN FIRE DISASTER PREVENTION SYSTEM TO ROAD TUNNELS IN JAPAN

Amano R.
University of Tokyo, Kajima Corporation, Japan
Kurioka H., Kuwana H., Murakami M.,
Kajima Corporation, Japan
Tsuruda T., Suzuki T., Ogawa Y.
National Research Institute of Fire and Disaster, Japan

ABSTRACT

With the enforcement of the Special Measures Act for Public Use of Deep Underground as well as with ongoing urban renewal, there is a need for fire disaster prevention technology to secure the occupants’ safety in case of fire breaking-out in any underground space.

In this respect, a fire disaster prevention system using a water screen was developed for potential fires in underground spaces. This system is aimed at securing the occupants’ integrity from the fire by partitioning the fire zone using a water screen and also at the safety of a structure by reducing damage due to the fire. It would correspond to the performance-based-design for providing refuge for the occupants.

In the paper to be prepared, results obtained from experiments on the characteristics of the water screen when used as partitioning technology will be described first. Next, the applicability of this water screen fire disaster prevention system to road tunnels will be examined.

Keywords: water screen, fire disaster prevention system, tunnel

1. INTRODUCTION

Although Japan has entered days of population decline, the demand for space in urban areas has greatly increased under the recognition of the importance of improved urban infrastructures. In order to cope with the decrease in population while maintaining the urban functions within limited areas, it is necessary to further improve the infrastructures of big cities. For that purpose, the Special Measures Act for Public Use of Deep Underground was enforced with the view of making full use of underground spaces and urban reproduction projects for effectively utilizing underground spaces with a depth of 40m or more have been carried forward.

However, it is difficult to take appropriate and prompt measures to meet with a fire breaking out in underground spaces where routes through which heat, smoke and particles can pass to the outside are limited.

Large-scale fires which broke out in tunnels such as the Euro Tunnel and the Mont Blanc Tunnel and at a subway station in Taegu city in Korea inflicted severe damage. Due to the fact that these spaces were enclosed and the supply of air from outside was limited, the occupants took refuge in a direction to which high temperature smoke spread and eventually big disasters occurred.
In cases where fires break out in tunnels or in underground spaces, it is very important to secure the “safety of structures” by restraining the spread and extension of flames while also cooling structures to ensure the “safety for evacuation” in order to isolate occupants from heat, smoke and any poisonous gases generated by a fire and to guide them to safe places.

In cases where fires break out in tunnels or in underground spaces, it is very important to secure the “safety of structures” by restraining the spread and extension of flames while also cooling structures to ensure the “safety for evacuation” in order to isolate occupants from heat, smoke and any poisonous gases generated by a fire and to guide them to safe places. Namely, for the purpose of protecting lives, it is necessary to keep the temperature and air quality in a range where survival is possible as well as to secure passageways of refuge for leading occupants from underground spaces through to the outside spaces. Furthermore, rescue teams must move in close to fire zones in safety. In the case of a fire breaking out in a tunnel, two different methods are taken into account; one for protecting lives throughout the tunnel and the other for protecting them in partially compartmented spaces. In Japan, a method for compartmenting a fire zone using water spraying equipment installed in road tunnels has been standardized. With regard to deep underground tunnels in big cities, highly developed monitoring and safety measures for protecting lives from earthquakes, flood damage and terrorist attacks must always be maintained. In this respect, a method for creating compartments while always maintaining the function for monitoring and safety is required.

A water screen fire disaster prevention system for improving the safety of occupants escaping from a fire in order to protect their lives by compartmenting a fire zone using water screens (hereafter referred to as WS), was developed.

The characteristics of this water screen fire disaster prevention system as well as emergency facilities of road tunnels in Japan are described below for the purpose of indicating the applicability of this new fire disaster prevention system to the existing systems in the future.

2. EMERGENCY FACILITIES OF ROAD TUNNELS IN JAPAN

2.1. Procession

On the night of July 11, 1979, the worst fire accident in Japanese history happened in the Nihonzaka Tunnel. 170 cars were caught in a fire that broke out in a tunnel with a length of 2045m on the Tomei [Tokyo-Nagoya] Expressway. 7 people were killed in this accident. Furthermore, the interruption of the Tomei Expressway, which is indispensable for the Japanese economy, inflicted a great economic loss.

Accordingly, the existing conception of the installation of emergency facilities for road tunnels in Japan was put in order to create the road tunnel emergency facilities installation standards in 1981 based on the lessons obtained from this accident. Later on, the standards were partially revised as a result of investigations carried out through fire tests in actual tunnels. Details of the road tunnel emergency facilities installation standard and explanations issued by the Japan Road Association in 2001 are described below.

2.2. Road tunnel emergency facilities

Road tunnels in Japan are classified into 5 ranks extending from class AA to class D depending upon the length of tunnels and traffic volume (Figure.1). Standards for the installation of emergency facilities are determined according to each classification rank. Namely, a scale for the extent of emergency facilities is decided upon due to the fire occurrence ratio for each tunnel. As for very long tunnels on national highways classed AA complete facilities must be installed.
Equipment for notification and alarm, extinguishment equipment, refuge instruction equipment and other pieces of equipment are installed as emergency facilities.

① Equipment for notification and alarm.
This equipment is used for notifying road management personnel, fire stations or police stations of the occurrence of a fire and other accidents in tunnels as well as for informing road users inside and outside the tunnels. Emergency telephones, push-bottom notification devices and fire detectors are all part of the notification equipment. Alarm equipment has emergency alarm devices (photo 1).
② Extinguishment equipment

Fire fighting implies initial fire fighting carried out by occupants in tunnels and full-scale fire fighting by fire-brigades. Extinguishment equipment including fire extinguishers and fire hydrants is installed assuming initial fire fighting.

③ Refuge instruction equipment

This equipment is used for guiding occupants who have met with a fire or accidents in tunnels for evacuation to the outside in safety.

There are guide sign plates, smoke exhaustion equipment and exit passageways included in the refuge instruction equipment. The guide sign plate indicates information with regard to distances to exits, the distances or directions to exit passageways and their locations.

The smoke exhaustion equipment restrains the spread of smoke in order to improve the environment for evacuation in the case of a fire breaking out in tunnels. It also compulsorily exhausts smoke permeating the whole tunnel to the outside in order to facilitate fire fighting and rescue • first aid activities easily. In general, ordinary ventilators are used for smoke exhaustion.

In the case of a longitudinal ventilation system being applied, a wind speed in a one-way traffic tunnel is set at 2m/s in order to restrain the spreading of smoke toward the windward side when a fire breaks out. Moreover, in a two-way traffic tunnel at the initial evacuation stage just after a fire has broken out, operation of ventilators is stopped in order to control the spreading of smoke. When fire fighting or rescue and first aid activities are carried out, ventilators are activated in order to exhaust smoke.

Exit passageways are used for guiding occupants in a tunnel to other safe spaces for evacuation.

④ Other pieces of equipment

Other pieces of equipment supplement equipment for notification and alarm, extinguishment equipment and refuge instruction equipment in order to carry out effective fire fighting. There are water taps, radio communication auxiliary equipment, radio rebroadcast equipment, loudspeaker, broadcast equipment, water spraying equipment and monitors as other pieces of equipment.
Water spraying equipment restrains the force of flames by cooling a fire source and its vicinity and supports fire fighting as well. Specifications of water spraying equipment were determined in 1968 based on the results of fire tests conducted in actual tunnels in 1960s. Since then, the specifications of water spraying equipment have been investigated through carrying out several model tests and fire tests in actual tunnels.

Emergency facilities for road tunnels in Japan have been installed on the basis of the aforementioned concept since the fire accidents happened in the Nihonzaka Tunnel. However, with regard to water spraying equipment, it has been pointed out that it may well be that the environment for evacuation will be deteriorated due to the spreading of smoke in the case of the water spraying equipment being activated at an early stage of a fire. It can be thought that when deep underground spaces are utilized in big cities in the future, technology to secure the safety of occupants there is necessary without fail.

Figure 2: Progress

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3. WATER SCREEN FIRE DISASTER PREVENTION SYSTEM

The water screen fire disaster prevention system was developed as technology for improving the safety of occupants taking refuge in the case of fires breaking out in tunnels or underground spaces. This system aims at securing the safety of occupants by compartmenting a fire zone using WS, restraining the spread of heat and smoke and seizing and washing out poisonous floating particles. It also can minimize the degree of damage to structures. This system is a technology for creating water screens by spraying water under high pressure in a hanging bell shape from spiral type water screen heads (photo 2) arranged in lines in patterns which form compartments.

![Photo 2: Spiral Head](image)

![Figure 3: Relationship between mean particle diameter and heat radiation](image)

### 3.1. Compartmenting using WS

Past studies have resulted in confirming the fact that the smaller a mean particle diameter and the slower a dropping speed for sprayed water under the condition of the same amount of water, the higher the heat radiation isolation effect (Figure 3). Furthermore, investigations were carried out under the condition of the mean particle diameter being 100 μm or more in order that the water particles may not be swept away by fire plumes or be vaporized.

As a result, WS with a mean water particle diameter of about 200 μm was developed as a new method for compartmenting a fire zone which has functions other than just the fire extinguishing performance of water sprinkling equipment, namely functions for fire prevention compartments and escape equipment. The water particle diameter of the WS is about 1/5 of about 1000 μm for the diameter of a rain particle and the diameter of a water particle from a sprinkler. In this case, the volume of a water particle sprayed from the WS is about 1/125 of rain or sprinkled water particles and the number of water particles corresponding to the same volume of water is about 125 times. The surface area of a water particle from the WS becomes about 1/2, so the total surface area for the same volume of water reaches 5 times. This new compartmenting method with WS was developed utilizing the fact that the dropping speed for water particles from the WS decreases and the heat radiation isolation effect is heightened. Moreover, the water screen can be created by using the effect of water particles with a diameter of about 200 μm (Figure 4).
This water screen can be formed by the water sprayed at 10L/min from each of the special spiral type heads in a hanging bell shape with a radius of about 800mm. Moreover, since the water is sprayed from each head in an almost horizontal direction under drainage pressure of about 1.0MP, there is no vacant space between the ceiling surface and the sprayed water surface.

**Sprinkler, Rain drop**
- Moving Speed: Fast
- Size: 1mm

**Water Screen**
- Moving Speed: Extremely NATURAL
- Size: 0.2mm

**Water Mist, Fog**
- Moving Speed: Slow
- Size: 0.05~0.1mm

*Figure 4: Comparison*

In cases where a fire breaks out in a tunnel under natural ventilation conditions, with regard to the flow in an axial direction, the flow of high temperature smoke floating toward an exit at the upper part of the tunnel becomes a function of a heat release rate from the fire source and it agrees with the flow of air moving in the reverse direction at the lower part of the tunnel in the mass flow flux. When actuating the WS installed at right angles to the longitudinal direction of a tunnel at fixed intervals, the density difference at the upper end of the flow becomes small due to a cooling effect of the WS upon the high temperature smoke layer. Accordingly, the flow stops and the effects of the compartment such as the decrease in heat radiation are exerted. Compartmenting is based upon the conception that heat and smoke generated by a fire should be confined within a limited area to prevent them from spreading in the whole space. Furthermore, it can be estimated that the water screen fire disaster prevention system has an effect to restrain the heat release rate due to the decrease in the air flowing in from the outside of the tunnel.

### 3.2. Characteristics of WS

In order to confirm the compartmenting effect of the WS in a road tunnel, a fire test was carried out (Photo 3) using a ventilation control wind speed (0~3.2m/s) and a gasoline fire source (corresponding to 8.5MW, 28.5MW) as main variables assuming tunnels of class AA for the Road Standards Type 1.

Radiant heat absorption characteristics as well as heat generation characteristics in the case of a compartmenting length being set at 50m were obtained. This fire test was carried out using a 1/2 scale model of a tunnel (Photo 4). Each variable used in the test was reduced based on the Froude law (Table 1). As a result of the test, the following compartment characteristics of the WS were obtained.

<table>
<thead>
<tr>
<th>Table 1 Coefficient of Reduced Scale</th>
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<tbody>
<tr>
<td>Typical Length</td>
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<tr>
<td>Wind velocity</td>
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<td>Heat Release Rate</td>
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<td>Time</td>
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<td>Interval of Head</td>
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3rd International Conference ‘Tunnel Safety and Ventilation’ 2006, Graz
Photo 3: Emergency Facilities

Photo 4: 1/2 Scale Model

Photo 5: Interior conditions
(Before WS are activated)

Photo 6: Interior conditions
(After WS are activated)

Figure 5: Ceiling Temperature
Figure 6: Smoke Density in the Test Site

① 70~80% for the reduction of heat, 60~80% for smoke and about 15% for poisonous gas (CO) were confirmed respectively.

② The water screen was formed at an inclination of 33° in the case of an actual scale conversion wind speed being 20m/s (test wind speed: 1.4m/s) and the same compartmenting effect as that mentioned above was confirmed.

③ A fire zone compartmented by WS can protect the lives of any occupants.

④ Evacuees can easily pass through water screens.

As mentioned above, it was verified that the WS is very effective as a technology for compartmenting a fire zone when a fire breaks out in tunnels.

3.3. Main Equipment of WS

The main equipment is relatively simple and consists of water supply units such as tanks, high pressure pumps and piping, and water screen spray nozzle heads connected to this as well as dedicated fire detectors and a control panel. It can easily in existing structures.
4. APPLICABILITY OF THE WS TO ROAD TUNNELS

Up to now, road tunnels have yet to be compartmented in order to avoid traffic congestion. However, the applicability of the WS to road tunnels as a compartment technology has been investigated in order that occupants may take refuge in safety and that fire-fighting • rescue operations may easily be carried out. This is so because the WS does not obstruct traffic and it also reduces heat and smoke in road tunnels.

A deep underground tunnel in urban districts is subjected to the investigation this time. A shield tunnel such as Tokyo wan aqua-line which is a representative underground tunnel structure in Japan was assumed.

Places of safety are located under floor decks. Air pressure is applied to these places for the purpose of preventing the inflow of heat and smoke from driveways. The basic safety of occupants can be secured if they take refuge in these places. Therefore, it is important to guide them to places of refuge in safety from the viewpoint of security of safety for evacuation.

A longitudinal ventilation system was applied to vertical shafts for air ventilation. A tunnel section area was set at 100m² or more. Water spraying equipment and WS were arranged at intervals of 5m and 50m respectively. Owing to the fact that in a tunnel the air flows toward a fixed direction due to effects of ventilation and the movement of vehicles, heat and smoke easily spread on the leeward. In particular, it is an important subject in tunnels in urban districts which are apt to be crowded with a great number of vehicles to check the spread of a fire for vehicles as well as to prevent the extension of damage caused by heat and smoke flowing on the leeward side.

The steps of procedure for the water screen fire disaster prevention system subjected to the investigations this time are as follows:
Figure 8: View of the system when applied to a road tunnel

Figure 9: Water screen fire prevention system for road tunnels

[Steps of procedure for the water screen fire disaster prevention system]
① A fire zone is to be specified after detecting the occurrence of a fire.
② A fire compartment is to be formed by actuating WS so that it can surround the location of the fire in order to reduce heat and smoke spreading to other zones.
In the case of a one-way traffic tunnel, the wind speed is controlled at 2m/s. In the case of a two-way traffic tunnel, the operation of the ventilators is stopped.
③ Occupants move to safe zones (safety zones) on the road surfaces where the effects of heat and smoke are small after passing through WS from a fire zone. Then, they move to places of safety located under the road surface going down slopes from fire exits and they take refuge on the outside of the tunnel.
④ After the occupants have moved to the outside of the fire zone through WS, water spraying equipment in the fire zone is to be activated for initial fire-fighting in order to cool tunnel structures.
5. Fire brigades enter onto road surfaces outside the fire zone going up slopes from places of safety under the floor decks and move in close to the fire zone. Fire–fighting and rescue operations are carried out after confirming actual conditions in the fire zone from various sources located on the outside of it. It can be taken into account whether to activate ventilators for smoke exhaustion without using WS depending upon conditions in the fire zone.

The safety of occupants moving to refuge can be improved in accordance with these steps of procedure.

5. CONCLUSION

In this paper, application examples of the water screen fire disaster prevention system as a technology for the compartmenting of road tunnels are described. However, the applicability of this system to railways tunnels, places for doors leading to places of refuge in the case of mountain tunnels and junctions of two tunnels.

Furthermore, in view of the fact that the time, in which occupants can take refuge in safety, can be quantified as the time for actuating WS, a rational design of a fire disaster prevention system including specifications of ventilation equipment and fire prevention equipment for the arrangement of places of safety can be made by combining the simulation of occupants’ actions for refuge and both a 3rd mode heat behavior analysis and a smoke flow analysis.

In the future, development for further improving this system will be carried out.

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