

The analyses and setting laws of escape channels in underwater road tunnels

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ABSTRACT: The problem of escaping from tunnels under fire has attracted more and more attention. It becomes a hot issue to imagine the escape design in the planning stage and to meet the escape-rescue requirements when the fire breaks out. Nowadays there are not specific criteria for escape designs in China, nor abroad. Although some researchers make use of numerical simulation methods to simulate fire scenarios with the purpose of designing the escape channels of certain tunnels, nobody sets general rules, especially the setting distance of connection tunnels. The authors try to collect information of forty tunnels at home and abroad, analyses the data, and try to find the relation between six parameters and the distribution of connection tunnels. The main objective, here, is to activate the research on setting laws on the design and distribution of connection tunnels in underwater road tunnels.

1 INTRODUCTION

With the development of underwater road tunnel construction, fire-proof section design has become more and more urgent and huge. Nowadays there are four methods to escape from tunnel when fire breaks out, they are service tunnel, connection tunnel, bottom escape channel and shaft. All of them have their respective characteristics and applied conditions. In the planning phase, it is a hot issue how to choose the proper escape way and how to distribute the connection tunnels. At present we do not have specific criteria on the setting laws of escape channels at home and abroad, just specific project-specific analysis. Domestic engineering specifications have only given the reference value of connection tunnel distance of road tunnels constructed by mining method^[1]. From the point of view of least people's evacuation time and available safe evacuation time, domestic and foreign scholars simulated the single tunnel on fire and achieved some useful conclusions^[2]. However, from a theoretical point of view, research on the general rules of setting escape channels is still blank.

Based on the above, the authors collect plenty of information of domestic and foreign tunnels, try to find the relation between parameters and escape channel's setting law in order to make progress on the research of fire-proof section design. I hope that it may give some suggestions to the tunnel design.

2 ROAD TUNNEL ESCAPE METHODS OVERVIEW

There are four escape ways in road tunnel construction at home and abroad, service tunnel, connection tunnel, bottom escape channel and shaft [3].

2.1 Service Tunnel

Service tunnel, which is built between two main tunnels, usually is constructed earlier than main tunnels. It can help to pretreat adverse geological condition, and do some improvement in advance while constructing the very long road tunnel. In the operation period, service tunnel can act as the emergency evacuation trenches through horizontal link way, when fire breaks out. Furthermore, it can be an overhaul lane, which is easy for maintenance. But the shortcomings are the increase of engineering cost and the complexity of the structure. Service tunnel is always applied in rock tunnels. It is shown in Fig.1.

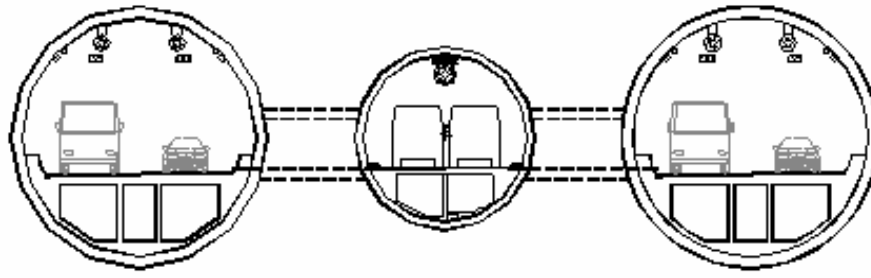


Fig.1 Service tunnel

2.2 Connection Tunnel

Connection tunnel can be seen as a simplification of service tunnel with respect to escape and rescue. When fire breaks out, the two main tunnels should be closed quickly, and evacuees should be evacuated to another channel, the security zone, through connection tunnel.

The merits of connection tunnel are high efficiency, fast evacuation, and good ventilation, while the weakness is bad load-bearing system, which is unable to meet seismic requirements, because of the open space on the sidewall. The cracks are easier to spread vertically as well. Compared with the service tunnel, the cost of connection tunnel is lower, but with high requirements of constructing technology, especially in soft ground. When the freezing method is used, it is easy to cause floating sand and piping. Also, when fire breaks out, two main tunnels influenced each other badly. It is shown in Fig.2.

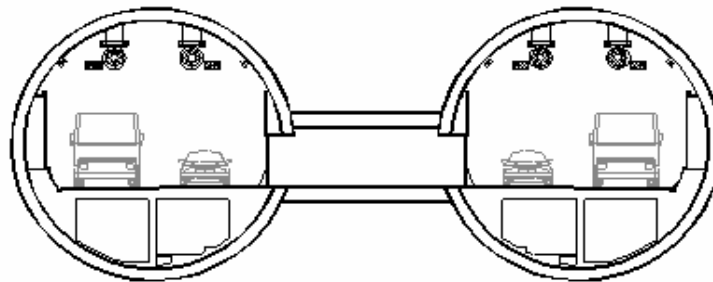


Fig.2 Connection tunnel

2.3 Bottom Escape Channel

It is an efficient way to make use of the surplus space under the lane. When fire breaks out, people can evacuate to the safety zone through slides and stairs. Evacuees can start from the safety entrance, pass the safety channel to finish the long-distance evacuation. The construction procedure is easy, and it is cheap. The entrance passing capacity is small. The evacuation capacity and size of the channel are greatly decided by the diameter of tunnel. The ventilation is bad. Evacuation path is long. It wastes some side space. However, the escape in one tunnel on fire does not influence the other tunnel. It is shown in Fig.3.

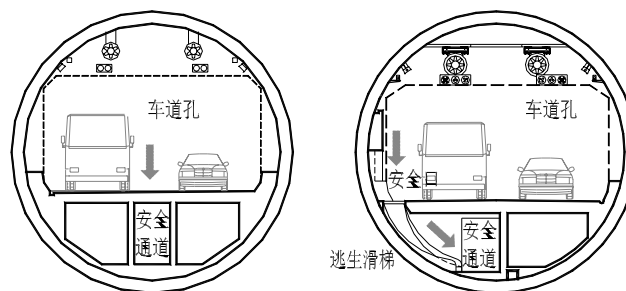


Fig.3 Bottom escape channel

The bottom escape channel is widely used in tunnel design with the increase of tunnel diameter and double-lay tunnel's application, because the evacuation capacity was restricted by diameter before. At first, The Tokyo Bay Tunnel planned to use the connection tunnel for evacuation. The depth of tunnel is 60 meters in soft clay, the two tunnels will deform differently under earthquake, thus the joint between the connection tunnel and round tunnel will be badly destroyed. Therefore, the designer decided to make use of bottom escape channel instead of connection tunnel. It makes good use of bottom space of tunnel. The distance of bottom channel is 300 meters. It is shown in Fig.4.



Fig.4 Tokyo Bay Tunnel section

2.4 Shaft

The shaft, which can lead evacuees to the ground, is usually used in the thin-covered urban road tunnels for evacuation. They are usually built as ventilation shafts as well, setting in a row. The shortcomings are low evacuation speed and small passing volume. A86 road tunnel in France sets refuges out of the tunnel with the distance of 400 meters, and evacuation stairs to the upper ground with the distance of 1200 meters. It is shown in Fig.5.

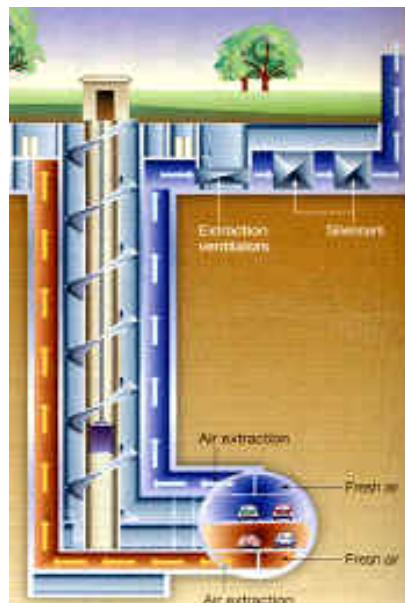


Fig.5 Evacuation shaft in A86 road tunnel in France

In the tunnel design, one or several escape methods are adopted. The Tokyo Bay Tunnel chose bottom escape channels and shafts to escape from fire in 1997. Qiantang River tunnel in China also adopts connection tunnels and bottom escape channels as the way of evacuation.

2.5 Comparison of Four Ways

Four ways of escaping have respective strong points and shortcomings, and they are used in different conditions. Service tunnel is good at passing capacity. But its application is restricted by high cost and mostly using in hard rock area. Connection tunnel is mostly used in tunnels at present because of its great evacuation capacity and low cost. But connection tunnel is harmful to the two main tunnels since it weakens the structure. It can not be used in bad geological conditions. With the increase of tunnel diameter and using of double-lay tunnel, bottom escape channel is gradually used widely. Because of its poor evacuation capacity, shaft tunnel is seldom used, and usually works as an assistant escape way. The table below gives comparison of four escaping ways.

Table 1 Comparison of four escaping ways

Escaping ways	Passing ability	Escape path	Construction difficulty	cost	Impact on other tunnels	ventilation	Set spacing
Service tunnel	best	short	general	highest	small	good	
Connection tunnel	better	short	Hard in soft clay area	higher	big	good	100m—500m
Bottom escape channel	worse	longer	none	lowest	none	bad	60m—80m
shaft	worst	longest	easy	higher	none	bad	Above 1000m

3 UNDERWATER ROAD TUNNEL CASES AT HOME AND ABROAD

Underwater road tunnels can be divided into four groups according to the construction methods. They are immersed tube tunnels, shield tunnels, mining tunnels and tunnels constructed by TBM. We mainly introduce the former two kinds of tunnels.

3.1 Immersed Tube Tunnels

Immersed tube tunnels are the ones which are constructed by immersed prefabricated steel pipes or concrete pipes to the bottom of the riverbed, and by recovering the soil on the top. They are applied in the soft clay areas. They have fast construction speed, short tunnel length, little geological restriction, and low cost of unit area.

In 1910 American engineers built Central Michigan Railway Tunnel crossing Detroit River. In 1914 New York Subway Tunnel was built crossing Harlem River. In 1928 the first concrete immersed tube road tunnel was built connecting Oakland of California and Alarcon. In 1930 the road tunnel, surface of which is octagon, was built connecting Detroit and Canada Wen Tesoriere. After America, the immersed tube tunnels are widely used in Europe and Japan. The most famous

one is San Francisco Bay tunnel (railway tunnel), which is a steel pipe tunnel, built in sandy soft clay. It is 5825 meters long, 14.58 meters wide, 6.55 meters high. The middle rectangle hole is used for maintenance tunnel as well as evacuation tunnel. The widest tunnel is Rupel in Belgium, the width of which is 53.1 meters. The first immersed tube tunnel in Europe is Holland Maas tunnel, which is built in 1942. Zeeburger tunnel in Holland is 26.7 meters wide, 7.2 meters high. Its section is rectangle. Tokyo road tunnel has Semi-horizontal ventilation system. Pusan-Juji road tunnel in South Korea is 3400 meters long, inside of which lays four lanes. There are service tunnel and connection tunnels for escaping.

Immersed tube tunnels in our country started late. They are mainly locating in Shanghai, Hongkong, Taiwan and Ningbo. Outer ring tunnel in Shanghai is 2880 meters long. It has three holes, and eight lanes in it. The middle hole works different with time. The 2-meter-width escape tunnel is set every 50 meters. Zhujiang tunnel is formed by 5 pipes. The section is divided by four holes, including subway lanes, car lanes and pipe lanes. Yongjiang tunnel is a two-lane tunnel using the vertical jet ventilation. Hong Kong-Kowloon Red Cross Harbor Tunnel is 1602 meters long under water. The ventilation system is transverse ventilation. There are 6 connection tunnels in every pipe. Eastern tunnel and Western tunnel were constructed in Hongkong one by one. Eastern tunnel equips with 26 connection tunnels, at 65-meter spacing. Transverse ventilation is used. The daily traffic design of Western tunnel is 180,000 cars per day, but only 39,700 cars per day in state business. Kaohsiung tunnel is 1550 meters long. Vertical ventilation is used.

3.2 Shield Tunnel

Shield method is also a very important construction method while building underwater tunnels, especially in soft clay. The first shield tunnel was built in Thames in London in 1843. And then the technology had been greatly improved, also materials became diversity.

Shield underwater road tunnels at abroad include England-France tunnel, Tokyo Bay tunnel, Germany Elbe tunnel, and Kingsway tunnel in England. England-France tunnel has its service tunnel in the middle. There are 3.3-meter-width connection tunnels every 375 meters. Tokyo Bay tunnel sets escape slides at 300 meters interval. Kingsway tunnel in England is 2.2 kilometers long, and sets connection tunnels every 350 meters.

Shield underwater tunnels in Shanghai are very prominent in China. They are introduced as follows. Dapu road tunnel is the first tunnel built in Shanghai. At that time, escape-rescue concept had not been involved. Yanan south road tunnel's escape channel is modified by a maintenance access, which can only allow one person to get through. Dalian road tunnel has two connection tunnels inside at 400 meters interval. The section of connection tunnel is 1.4 meters wide, 2.7 meters high. At the same time the tunnel sets bottom escape channel every 30 meters, whose entrance is located in the center of the road. Xiangyin road tunnel sets 13-meter-long connection tunnels every 500 meters, and sets escape slides at 80 meters interval. Fuxing eastern road tunnel is a two-layer tunnel. It has two car-lanes in the upper layer, and has a large-bus lane and an emergency stopping lane in the lower layer. It has connection tunnels every 432 meters, whose section is 1.5 meters wide, 2.4 meters high. It also sets bottom escape channels at 60 meters interval. Shangzhong road tunnel is another two-layer tunnel in Shanghai. But it does not set connection tunnels as an escaping way. Instead, it has escape stairs at 60 meters interval. Shanghai Yangtze River tunnel, which is still under construction, sets connection tunnels at 830 meters interval. Meanwhile, the tunnel has reserved a rail transit tunnel. Road and rail transit layer are located between three evacuation stairs, spacing 280 meters. Evacuees in the road

layer can escape through connection tunnels and evacuation stairs. Jungong road tunnel is still under planning. It will set four connection tunnels and evacuation stairs at 80 meters interval.

Furthermore, Wuhan Yangtze River tunnel, Nanjing Yangtze River tunnel and Qiantang River tunnel are tunnels built by shield machine. They all set connection tunnels or escape stairs for evacuation.

4 THE FACTORS AND SETTING LAWS OF CONNECTION TUNNELS IN UNDERWATER ROAD TUNNELS

Based on the former study, the authors collect information of nearly forty underwater road tunnels, including tunnel's diameter, length, number of carriageway, allowable velocity, volume per hour, acclivity, and evacuation ways. By analyzing these data, the authors get the factors which influence the choosing of evacuation way, and gain the rules of setting connection tunnels.

The ratios of four escaping ways are shown in Fig.6. They were achieved through the analysis of the underwater road tunnel cases.

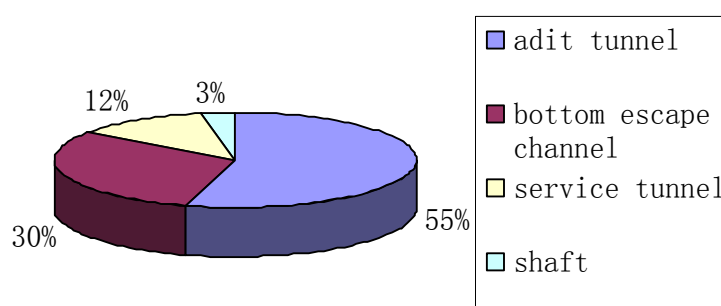


Fig.6 Ratios of four escaping ways

We may see that 55% of the tunnels adopt connection tunnels as an escape way, and 30% of the tunnels use the bottom escape channels. So we only analyze the two ways in the latter part.

The factors determining the setting of connection tunnels can be summarized as traffic density, traffic types, staff density, tunnel ventilation conditions, lighting, construction and maintenance costs and so on[4]. From the visual point of view, traffic accidents or tunnel fire accidents is proportional to volume of the tunnel. So, the tunnels with bigger volume of vehicles should have more connection tunnels than the ones with less volume of vehicles. If mixed traffic (passenger cars and trucks) is allowed in the tunnels, the probability of fire bursting out is much higher than in the tunnels allowing only passenger cars passing. High staff density tunnels need more connection tunnels. If the ventilation system can effectively make the spread of smoke under control, the spacing of connection tunnels can be increased accordingly. Escape velocity is greatly impacted by lighting, so lighting is a factor to the setting of connection tunnels. Because setting connection tunnels can increase the cost of project, construction and maintenance cost is another factor influenced the setting of connection tunnels.

Figures of the relation between area and distance, length and distance, velocity and distance, number of carriageway and distance, acclivity and distance, volume of vehicles and distance are shown in Fig.7-12. Appendix 1 shows the basic information of main tunnels.

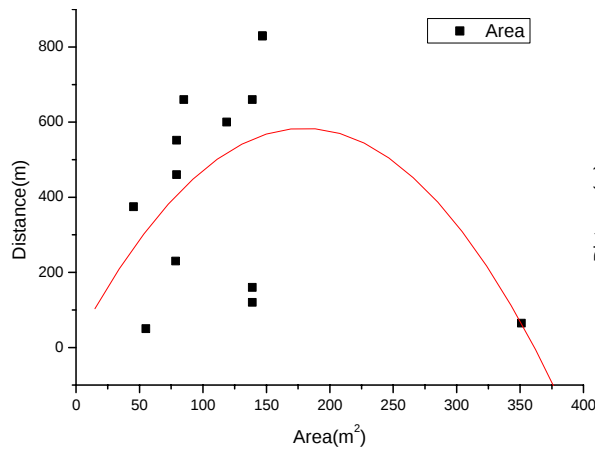


Fig.7 Area-distance relation

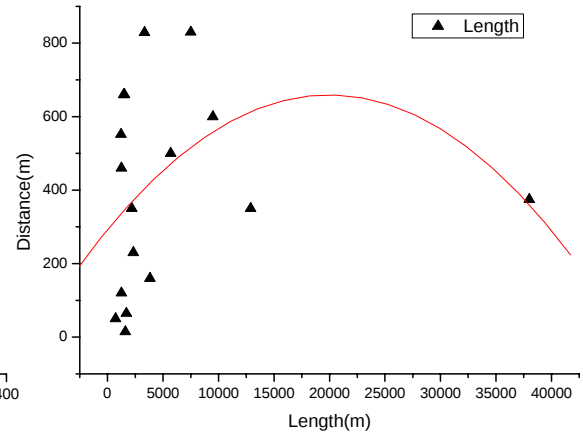


Fig.8 Length-distance relation

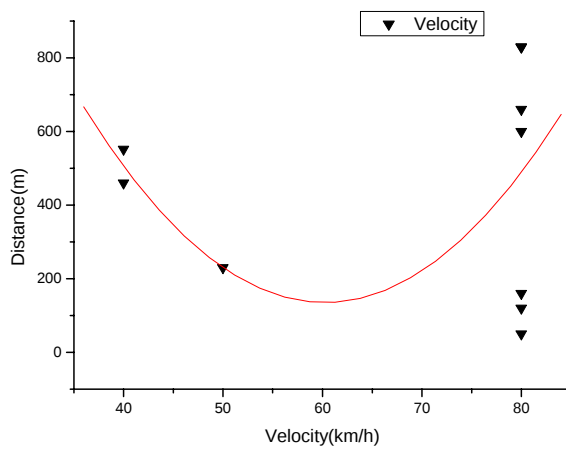


Fig.9 Velocity-distance relation

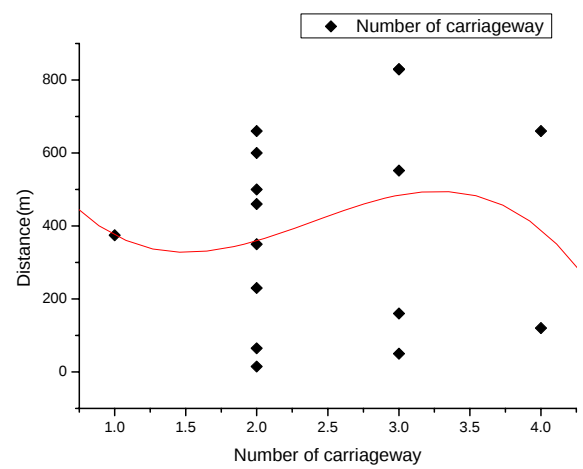


Fig.10 Number of
carriageway-distance relation

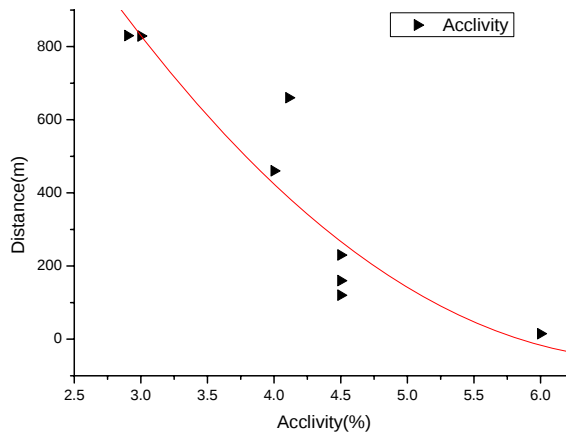


Fig.11 Acclivity-distance relation

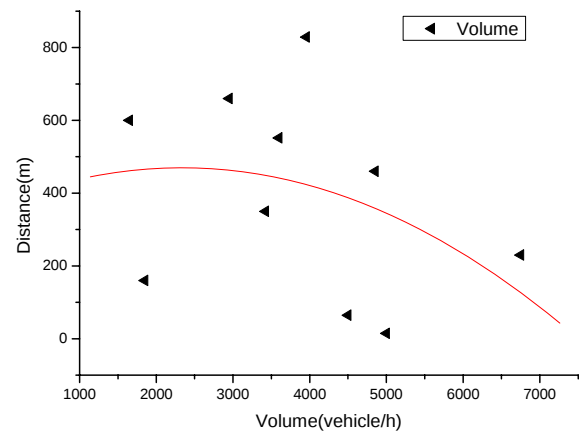


Fig.12 Volume-distance relation

Because the passing capacity of bottom evacuation channels is 1/3~1/2 of the capacity of connection tunnels, here we combined the two ways to gain the new distribution of connection tunnels. The figures above also follow this rule.

We may get several conclusions. With the increase of section area, the distance of connection

tunnels increases first, and then decreases. The peak value is for tunnels of 200 m² section areas. Ordinary tunnel section is smaller than 200m², so with the increase of section area, the distance of connection tunnels increases within a limit.

With the increase of tunnel length, the distance of connection tunnels increases first, and then decreases. The peak value is for the tunnel of 20000 meters long. Ordinary tunnel length is shorter than 20000 meters, so with the increase of tunnel length, the distance of connection tunnels increases within a limit.

With the increase of allowable velocity, the distance of connection tunnels decreases first, and then increases. The greater speed of vehicles, the more emissions of air pollutants. They add the difficulties of evacuation when fire breaks out. The spacing should decrease. Endless decreasing of spacing will causes high cost. So the distance increases gradually.

The number of carriageway and spacing of connection tunnels can be done with three fitting function curve, but with some deviations. In Fig.10, we may gain the conclusion that the spacing of connection tunnels has little things to do with number of carriageway. They are in the range of 200 meters to 600 meters.

The distance of connection tunnels decreases with the increase of acclivity. Bigger acclivity causes more pollutants. So the spacing should decrease. But it should have a minimum value. The least spacing is 15 meters, which is the spacing of connection tunnels in immersed tube tunnels.

With the increase of volume of vehicles, the distance of connection tunnels decreases gradually. It is easy to understand.

However, the complex relation between these factors needs further study.

The distance of connection tunnels is 200 meters to 600 meters in both mining road tunnels and underwater shield road tunnels. It is different from the limited value of 250 meters to 300 meters, which is applied in underwater transportation tunnels in urban areas. Also it is different from the limited value of 250 meters to 500 meters, which is applied in mining tunnels. The distance of connection tunnels in immersed tube tunnels is 50 meters.

The size of the connection tunnels is 2 meters or 3 meters. Two or three persons can pass through. The evacuation slides and stairs have the similar set.

5 CONCLUSION

First of all, four escape ways are illustrated and compared. Several underwater road tunnel cases are collected and studied in the second part. Then the authors gain the factors influencing the setting of connection tunnels, which is the most widely used escape way. Some preliminary and important conclusions are achieved on the relation between distance of connection tunnels and the basic parameters of tunnels. To be specific, they are tunnel diameter, length, velocity, number of carriageway, acclivity and volume.

The shortcoming of this paper is no considering of ventilation. In the future work, authors will collect more information, modify the conclusions by adding the soil parameters, with the purpose of getting better fitting curve, and revealing better laws.

REFERENCES

Code for design of road tunnels. S. Chongqing transportation scientific research and design institute,

2004 (in Chinese).

Yang Gaoshang, An Yonglin, Peng Limin et al.(2006) Simulation of how people escape from tunnel fire. *J. Hazard.* 21(4):8-13.(in Chinese).

Huang Hongwei(2006). The risk evaluation of Qiantang River tunnel-fire prevention. R. *Geotechnical engineering of Tongji University*.(in Chinese).

He Chunning, Qiao Zongzhao, Shen Jieqing(2005). The setting laws of connection tunnels. *J. Underground works and tunnels.* 3:53-56.(in Chinese).

Appendix 1 the tunnel cases mainly involved

Cases	Diameter(m)	Length in the water(m)	Velocity(km/h)	Number of carriageway	Acclivity	Volume of vehicles(vehicles /hour)	Escape way	Distance and size
Dalian road tunnel	10.04	1253	40	2	4%	4854	2 connection tunnels + bottom escape channels	400m(2.7m×1.4m) +30m
Xiangyin road tunnel	10.4	1523	80	2			2 connection tunnels +escape slides(side)	500m+80m
Fuxing eastern road tunnel	10.04	1214	40	2+1		3600, actually 1800 in state business	4 connection tunnels +bottom escape channels	432m(2.4m×1.5m) +60m
Shangzhong road tunnel	13.3	1250	80	2+2	4.50%		Escape slides	60m(250mm×160m m)
Shanghai Yangtze River tunnel	13.7	7500	80	3	2.90%		8 connection tunnels+ bottom escape stairs	830m
Jungong road tunnel	13.3	1475	80	2+2	4.11%	2950	4 connection tunnels + evacuation stairs	500m+80m

Cases	Diameter(m)	Length in the water(m)	Velocity(km/h)	Number of carriageway	Acclivity	Volume of vehicles(vehicles /hour)	Escape way	Distance and size
Wuhan Yangtze River tunnel	10	2321	50	2	4.50%	6750	10 connection tunnels + escape slides on the side	230m
Qiantang River tunnel	13.7	3340	80	3	3%	79149 per day	Escape slides + connection tunnels	80-100m+ 669m
Nanjing Yangtze River tunnel	13.3	3825	80	3	4.50%	37000 per day	Escape slides	80m
England-France tunnel	7.6	38000		1			Connection tunnels + service tunnel	375m
Tokyo Bay tunnel	12.3	9500	80	2		33000 per day	Escape slides + shafts	300m
Kingsway tunnel		2200		2		25 million per year	3 connection tunnels	350m(2.46×2.4)
Taiwan Pinglin tunnel		12900					Connection tunnels	350m

Cases	Diameter(m)	Length in the water(m)	Velocity(km/h)	Number of carriageway	Acclivity	Volume of vehicles(vehicles /hour)	Escape way	Distance and size
Strenger tunnel		5700		2			Connection tunnels	500m(3.5×3.1)
Outer ring road tunnel	Middle hole 5.5(height)×7.5, side hole 5×11	736	80	3			Safety evacuation channels	50m
Hongkong eastern tunnel	9.75×36	1700		2		90000 per day	26 connection tunnels	65m
Hong Kong - Kowloon Red Cross Harbor Tunnel	6.7(lane)	1602		2	6.00%	100000 per day	Connection tunnels	6 connection tunnels in every pipe(100m long)