扎尕梁特长公路隧道通风方案比选研究

李志鹏

(山西省交通科学研究院, 山西 太原 030006)

摘要: 为找到一种更加适合单洞双向行车特长公路隧道的通风方案,解决此类隧道排烟困难、人员疏散逃生困难的问题,结合具体工程,针对扎尕梁特长公路隧道的特点,提出合流型通风井排出式+射流风机纵向通风、平导压入式网络通风以及射流风机纵向通风+斜井分段排烟3种通风方案,从土建费用、机电设备初期投资、运营电费、通风控制、通风网络稳定性、通风方案的适用性以及管理维护几个方面对各个通风方案进行比选,通过比较各个方案的优点和缺点,最终给出推荐方案:射流风机纵向通风+斜井分段排烟方案。隧道正常运营工况下,主洞采用全射流纵向通风,实现按需通风;火灾工况下利用排烟斜井进行排烟,解决平导排烟只能分2段排烟的问题;利用平行导洞进行人员的疏散逃生和救援,解决人员疏散逃生问题。

关键词: 公路隧道; 单洞双向行车; 隧道通风; 分段排烟

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Comparison and Selection of Ventilation Schemes for Zhagaliang Extra-long Highway Tunnel

LI Zhipeng

(*Shanxi Transportation Research Institute*, *Taiyuan* 030006, *Shanxi*, *China*)

Abstract: In order to select a suitable ventilation scheme for a single-tube extra-long highway tunnel with two-way traffic, as well as to solve problems in smoke exhaust and personnel evacuation in such tunnel, 3 ventilation schemes are proposed. According to the characteristics of Zhagaliang extra-long highway tunnel, the 3 ventilation schemes include confluent ventilation with exhaust shaft and longitudinal ventilation with jet fans, parallel pilot tunnel forced ventilation network, and longitudinal ventilation with jet fans and sectional smoke exhaust by inclined shaft. The ventilation schemes are compared from several aspects, i.e. civil construction cost, initial investment of mechanical and electrical equipment, electricity cost during tunnel operation, ventilation control, stability of ventilation network, applicability, management and maintenance. Finally, the most suitable ventilation scheme is selected by comparing the advantages and disadvantages of each scheme, i.e. longitudinal ventilation with jet fans and sectional smoke exhaust by inclined shaft. Under the normal operation condition of the tunnel, longitudinal ventilation with jet fans is adopted in the main tunnel, and on-demand ventilation can be realized. Smoke can be exhausted by inclined shaft in case of fire, which can solve the problem of smoke exhaust only in two sections by the parallel pilot tunnel. The parallel pilot tunnel can also be used for personnel evacuation and rescue.

Keywords: highway tunnel; single-tube two-way traffic; tunnel ventilation; sectional smoke exhaust

0 引言

目前,随着国内公路隧道数量的不断增加,单洞双向行车特长公路隧道所占的比例也越来越大。与双洞单向行车公路隧道相比,单洞双向行车公路隧道发生

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作者简介: 李志鹏(1982—),男,山西祁县人,2009年毕业于太原理工大学,信号与信息处理专业,硕士,高级工程师,现主要从事高速公路机电设计及科研工作。E-mail: 52968861@qq.com。

火灾的概率更大，根据相关统计分析大约要高 40%[1]。

国外大部分单洞双向特长公路隧道采用横向或半横向通风，全横向和半横向通风对于隧道通风排烟效果均是最好的选择，其缺点是初期投资大、后期维护不便、运营费用高，新建的隧道已经很少采用这种方式。

而国内单洞双向特长公路隧道主要采用平行导洞压入式网络通风，刘彤等[2]首次将平导送风型半横向式通风系统运用于二郎山隧道（4 176 m）；曾艳华等[3-4]在鹧鸪山隧道（4 448 m）将该方案进行了优化；金文良等[5]应用隧道通风网络解算程序，对雪峰山隧道的通风方案进行计算分析；彭伟等[6]基于行人与车辆单独疏散的原则，依托二郎山隧道提出了具体的火灾排烟和人车疏散方案；杨洪[7]依托白芷山隧道（6 710 m），综合采用理论分析、数值模拟、网络分析等手段研究了平导压入式网络风流稳定性；严涛等[8]依托巴朗山隧道（7 954 m）研究了横通道打开数量对通风网络的影响；蒋琪[9]针对单洞双向公路隧道研究了火灾通风排烟控制策略；王明年等[10]、严涛[11]针对高海拔地区单洞双向特长公路隧道研究了防灾与通风节能技术；陈汉波[12]、屈建荣[13]、陈诗明[14]针对单洞双向特长公路隧道研究了火灾时人员疏散救援的问题。2014 年 7 月《公路隧道通风设计细则》发布以后，要求纵向排烟的单洞双向交通隧道在进行火灾排烟设计时，应遵循火灾烟雾在隧道内的最大行程不宜大于 3 000 m 的原则[15-16]，平行导洞压入式网络通风不适用于超过 6 000 m 的隧道。

随着单洞双向特长公路隧道运营经验的积累，发现平行导洞压入式网络通风存在通风控制较复杂、通风网络稳定性较差[7-8]、通风方案的适用性受限制等问题，对隧道的安全运营产生了一定的隐患。针对此类隧道是否有更好的通风方案，使得隧道的建设运营成本和人员安全达到很好的平衡，已成为设计人员必须认真研究的问题。

1　工程概况

舟曲立节至四川永和公路建设工程 ZYZCB-2 标段起点里程为 K99+929，终点里程为 K156+420，路线全长 56.491 km。扎尕梁隧道属于该路段的控制性工程，布设于舟曲县博峪乡扎尕梁，隧道起点里程为 K123+066，终点里程为 K128+848，总长 5 782 m，最大埋深约 965 m。隧道小桩号侧坡度为 1.9%，坡长 4 705 m，设计标高 2 463.437 m；大桩号侧坡度为-0.5%，坡长 1 640 m，设计标高 2 535.762 m，变坡点在 K127+675 处。

根据《舟曲立节至四川永和公路建设工程可行性研究报告》对交通量的预测，扎尕梁隧道路段近、远期预测交通量换算结果见表 1。车型组成及比例见表 2。

表 1　隧道交通量计算

Table 1　Traffic volume in Zhagaliang Tunnel

所在路段	2025 年		2032 年	
	标准小客车日交通量/（pcu/d）	高峰小时交通量/（veh/h）	标准小客车日交通量/（pcu/d）	高峰小时交通量/（veh/h）
曲告纳—永和	1 181	110	1 758	164

表 2　车型组成及比例

Table 2　Composition and proportion of various vehicle types

%

年份	小货车	中货车	大货车	拖挂车	小客车	大中客车
2025	20.59	16.18	13.98	1.96	27.45	19.85
2032	20.39	17.78	14.54	2.26	26.68	18.35

扎尕梁隧道的主要技术参数如下：1）道路等级为三级公路；2）交通方式为双向两车道交通；3）设计行车速度为 40 km/h；4）交通量方向不均匀系数为 0.52；5）设计高峰小时交通量系数为 0.12；6）隧道断面面积为 57.85 m^2，周长为 19.29 m；7）隧道风速不宜大于 10 m/s。

2　需风量的计算

确定需风量时，应对稀释烟尘、CO 按 40、30、20、10 km/h 的行车速度工况分别进行计算，并计算交通

阻滞、换气和火灾工况的需风量,取其较大者作为设计需风量,阻滞段按每车道长度 1 000 m 计算。

2.1 稀释烟尘基准排放量

2000 年的机动车尾排有害气体中烟尘的基准排放量取 2.0 $m^2/(veh \cdot km)$。可分别得出本项目隧道设计近期 2025 年烟尘的基准排放量为 $2\times(1-0.02)^{25}$;设计远期 2032 年烟尘的基准排放量为 $2\times(1-0.02)^{30}$。

2.2 稀释 CO 基准排放量

正常交通时,2000 年的机动车尾排有害气体中 CO 的基准排放量应取 0.007 $m^3/(veh \cdot km)$;交通阻滞时车辆按照怠速考虑,2000 年的机动车尾排有害气体中 CO 的基准排放量应取 0.015 $m^3/(veh \cdot km)$,且阻滞段的计算长度不宜大于 1 000 m。

本项目中,设计近期 2025 年 CO 的基准排放量为 $0.007\times(1-0.02)^{25}$;设计远期 2032 年 CO 的基准排放量为 $0.007\times(1-0.02)^{30}$。

2.3 隧道换气需风量

隧道换气需风量应按照以下公式进行计算:

$$Q_{req(ac)}=\frac{A_r \cdot l \cdot n_s}{3\ 600}。 \quad (1)$$

式中:$Q_{req(ac)}$ 为隧道换气需风量,m^3/s;A_r 为隧道净空断面积,m^2;l 为隧道长度,m;n_s 为隧道最小换气频率,次/h。

2.4 火灾工况需风量

火灾工况需风量按照以下公式进行计算:

$$Q_{req(f)}=v_f \cdot A_r。 \quad (2)$$

式中:$Q_{req(f)}$ 为火灾工况需风量,m^3/s;v_f 为火灾控制风速,m/s。

2.5 需风量计算结果

通过计算得到扎尕梁隧道设计近期和设计远期对应的设计需风量见表 3。由表 3 可知,该隧道近、远期的控制工况均为稀释异味工况(即换气工况),所以通风系统按照稀释异味需风量一次设计,一次实施。

表 3 设计近、远期隧道对应不同控制指标的设计需风量

Table 3 Air demand for different control indicators in the short and long term m^3/s

设计工况	2025 年		2032 年	
	CO	烟尘	CO	烟尘
40 km/h	74.12	78.32	76.13	83.96
30 km/h	63.47	47.74	67.68	53.08
20 km/h(阻滞工况)	97.54	55.28	101.51	61.52
10 km/h(阻滞工况)	68.35	58.79	70.04	64.67
稀释异味工况	372.17		372.17	
火灾工况	173.55		173.55	

3 通风计算

通风系统中,风机及交通通风力提供的风量和风压应满足需风量和克服通风阻力的要求。

1)隧道自然通风力:扎尕梁隧道将自然通风力作为隧道通风阻力考虑;自然风作用引起的洞内风速取 3.0 m/s。

2)隧道交通通风力:扎尕梁隧道是双向交通隧道,交通通风力作为阻力考虑,并按设计车速以下各工况车速分别计算。

3)隧道通风摩阻力与风道损失:在具体计算过程中取值,根据隧道不同部位、不风道形式、角度等取值也不同。

4)隧道火灾排烟工况:考虑火风压的影响。

5)射流风机升压力:采用全射流纵向通风方式时,在隧道内风流稳定情况下,射流风机增加的风压与隧道内的自然通风力、交通通风力和隧道通风阻力相平衡。

4 通风方案

4.1 合流型通风井排出式+射流风机纵向通风(方案 1)

根据表 3 的计算结果可知,扎尕梁隧道近、远期的需风量均由稀释异味的需风量决定。由于近、远期扎尕梁隧道的控制需风量均为稀释异味的需风量 372.17 m^3/s,所以将 372.17 m^3/s 作为设计需风量,通风系统一次设计,一次实施。通过计算可知,扎尕梁隧

道采用全射流风机纵向通风即可满足正常运营工况下的通风要求,需要射流风机 32 台。考虑到火灾烟雾在隧道内的最大行程不宜大于 3 000 m,故需设置 1 处通风井。

扎尕梁隧道山体较宽厚,地形复杂,埋深较大,通风井与主洞的交叉位置只能位于隧道中段 218 m 范围内(K125+848~K126+066),此范围内隧道的埋深在 881.361~933.820 m。如果设置竖井,竖井深度过大,施工困难,无便道,不论从施工安全还是工程造价考虑均无有利条件,且该区域处于自然环境保护核心区,不能办理施工手续,所以放弃竖井方案;如果设置斜井,斜井稍长,施工难度一般,有可利用的便道。故结合扎尕梁隧道地形、地质、几何线形、工程经济等多方面因素,在隧道 K126+000 处设置 1 处排风斜井,将隧道分为 2 934 m 和 2 848 m 2 段,保证该隧道火灾排烟要求。

扎尕梁隧道通风方案 1 将斜井用于正常通风及火灾排烟,故采用合流型通风斜井排出式+射流风机纵向通风,通风区段划分为 2 段。为了满足人员逃生及救援需要,在隧道主洞的北侧设置平行导洞,并设置间距不超 500 m 的横通道。通风方案 1 如图 1 所示。

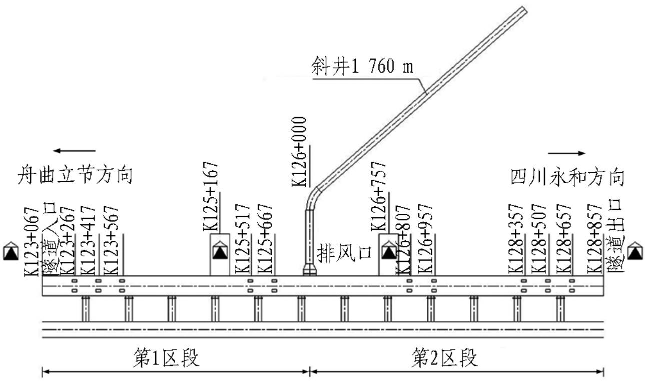

图 1　扎尕梁隧道通风方案 1 平面示意图

Fig. 1　Plan view of ventilation scheme 1 for Zhagaliang Tunnel

该方案斜井长度为 1 760 m,坡度为 12%,净空断面积为 27.98 m^2,隧道轴流风机房采用地上风机房。斜井及风道参数见表 4。

表 4　扎尕梁隧道斜井及风道参数(方案 1)

Table 4　Parameters of inclined shaft parameters and air duct for Zhagaliang Tunnel (Scheme 1)

斜井类型	排风口位置	斜井长度/m	斜井坡度/%	斜井净空断面积/m^2	斜井当量直径/m	斜井底联络风道长度/m	风机房类型
排风井	K126+000	1 760	12	27.98	5.78	55	地上

射流风机选用直径 1 120 mm、单机功率 30 kW 的双向射流风机;送、排风机采用大风量、低风压、静叶可调的轴流风机。

轴流风机功率的计算应结合风机的风压、风量的特点,选用的轴流风机经济、可行,并考虑一定的富余。通过计算,轴流风机装载总功率为 827.3 kW,选用 3 台 280 kW 的轴流风机;同时,隧道主洞需要再设置 20 台射流风机进行调压。当隧道内发生火灾时,为保证隧道火灾临界风速为 3 m/s,在不开启轴流风机的情况下,以射流风机提供推力,对火灾工况进行验算,需要设置射流风机 16 台。最后得出整个隧道通风系统风机配置见表 5。

表 5　扎尕梁隧道风机配置(方案 1)

Table 5　Fan configuration for Zhagaliang Tunnel (Scheme 1)

类型	位置	功率/kW	台数	功率小计/kW	功率合计/kW
射流风机	第 1 区段	30	10	600	1 440
	第 2 区段	30	10		
轴流风机	斜井	280	3	840	

4.2　平行导洞压入式网络通风(方案 2)

扎尕梁隧道通风方案 2 利用在隧道北侧设置的平行导洞进行通风、排烟。导洞的两端分别设置 1 处风机房,内置轴流送风机 220 kW 各 1 台,主洞设置 30 kW 调压射流风机 20 台。正常运营工况下,轴流风机将洞外的新鲜空气通过平行导洞和横通道均匀地送入隧道主洞中,主洞风流方向在中间部位的 6# 横通道处一分为二,分别向隧道入口和出口方向送风。

火灾工况时,隧道主洞作为排烟通道,排烟方式为分段排烟,烟雾在隧道中的行程为 2 900 m 和 2 849 m,均满足规范要求,人员则通过平行导洞进行疏散逃生。刚开始疏散阶段轴流风机应调小风量,满足横通道内的风压为正压即可;确定人员撤离完毕后,进入排烟阶段可调大风量,消防人员可从主洞一端进入火灾现场进行专业灭火。

事故工况时,救援车辆可以通过平行导洞进入隧道事故地点进行快速处理,避免人员在隧道内滞留时间过久。通风方案 2 如图 2 所示。

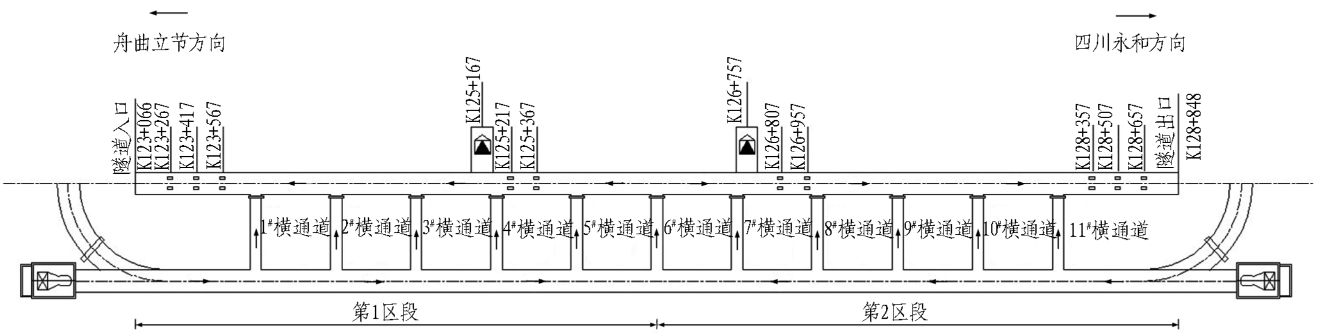

图 2　扎尕梁隧道通风方案 2 平面示意图

Fig. 2　Schematic diagram of ventilation scheme 2 for Zhagaliang Tunnel

通风方案 2 通风系统风机配置见表 6。

表 6　扎尕梁隧道风机配置表(方案 2)

Table 6　Fan configuration in the Zhagaliang tunnel (Scheme 2)

类型	位置	功率/kW	台数	功率小计/kW	功率合计/kW
射流风机	第 1 区段	30	10	600	1 040
	第 2 区段	30	10		
轴流风机	平行导洞	220	2	440	

4.3　射流风机纵向通风+斜井分段排烟(方案 3)

扎尕梁隧道通风方案 3 在正常运营工况时主洞采用射流风机纵向通风,火灾工况时利用排烟斜井进行排烟,并利用平行导洞进行人员的疏散逃生和救援。通风方案 3 如图 3 所示。

该通风方案在运营工况时,通过 32 台射流风机纵向通风来满足隧道新鲜空气的补给;火灾工况时利用斜井分段排烟来实现火灾烟雾在隧道内的最大行程不大于 3 000 m 的要求,平行导洞可以满足人员疏散逃生及救援的要求。

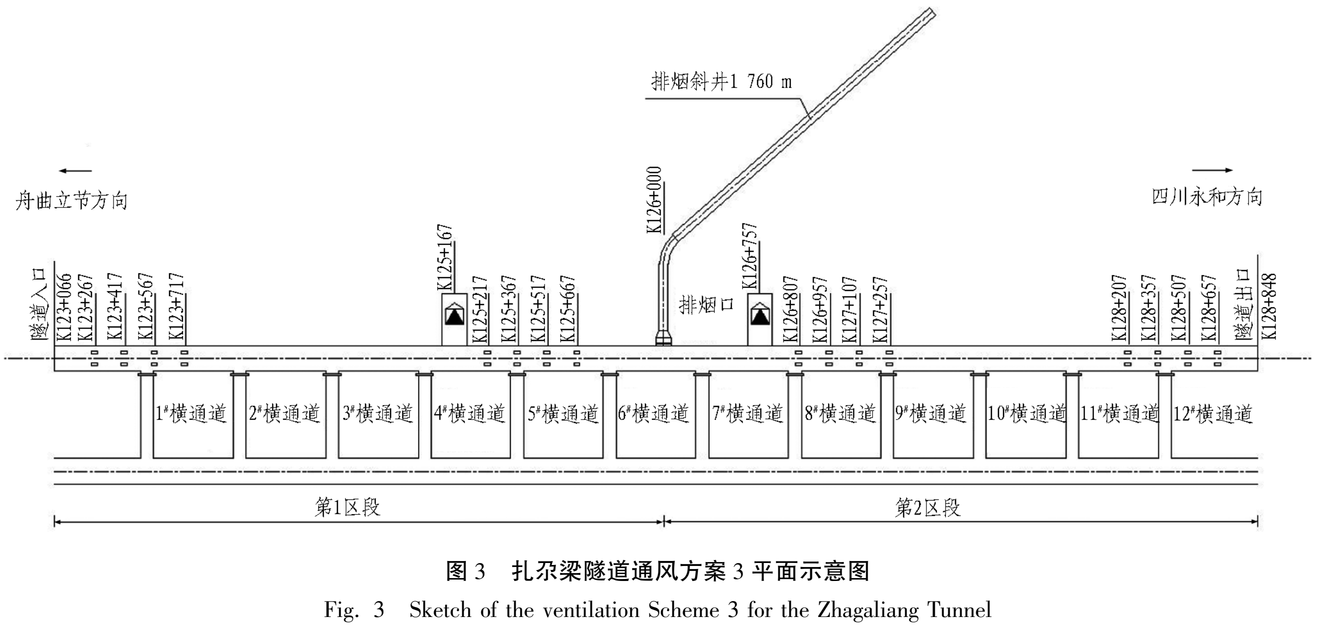

图 3　扎尕梁隧道通风方案 3 平面示意图

Fig. 3　Sketch of the ventilation Scheme 3 for the Zhagaliang Tunnel

该方案排烟斜井长度为 1 760 m,坡度为 12%,净空断面积为 13.35 m^2,隧道轴流风机房采用地上风机房。斜井及风道参数见表 7。

通过计算得到轴流风机装载总功率为 327.4 kW,选用 2 台 180 kW 的轴流风机;同时,隧道主洞需要再设置 16 台射流风机进行调压。最后得出整个隧道通风系统风机配置见表 8。

表 7　扎尕梁隧道斜井及风道参数(方案 3)

Table 7　Parameters of inclined shaft parameters and air duct for Zhagaliang Tunnel (Scheme 3)

斜井类型	排风口位置	斜井长度/m	斜井坡度/%	斜井净空断面积/m^2	斜井当量直径/m	斜井底联络风道长度/m	风机房类型
排烟井	K126+000	1 760	12	13.35	3.6	55	地上

表 8　扎尕梁隧道风机配置表(方案 3)

Table 8　Fan configuration for Zhagaliang Tunnel (Scheme 3)

类型	位置	功率/kW	台数	功率小计/kW	功率合计/kW
射流风机	第 1 区段	30	18	960	1 320
	第 2 区段	30	18		
轴流风机	排烟斜井	180	2	360	

4.4　方案比选

下面主要从土建费用、机电设备初期投资、运营电费、通风控制、通风网络稳定性、通风方案的适用性以及管理维护几个方面对扎尕梁隧道的通风方案进行比选,土建费用主要包括通风斜井(排烟斜井)、联络风道、风机房和便道的费用比较。比较结果见表 9。

表 9　土建费用比较表

Table 9　Comparison of civil construction cost

方案	斜井		联络风道		风机房		便道		费用合计/万元
	长度/延米	费用/万元	长度/延米	费用/万元	面积/m^2	费用/万元	长度/延米	费用/万元	
1	1 760	5 808	55	145.75	410	205	1.5	300	6 458.75
2	0	0	0	0	367	183.5	0.2	40	223.5
3	1 760	3 696	55	145.75	268	134	1.5	300	4 275.75

机电设备初期投资主要考虑射流风机和轴流风机的初期投资;运营用电费按照 20 年,每年按 365 d,每天风机平均运行时间为 10 h,电费 1.0 元/(kW · h)计算。通风方案比选计算结果见表 10。

表 10　通风方案比选计算结果表

Table 10　Comparison and selection of ventilation schemes

方案	土建工程费用/万元	设备初期投资/万元	20 年运营用电费/万元	通风控制	通风网络稳定性	通风方案的适用性	管理维护
1	6 458.75	452	10 512	较易	较好	长度不限	较易
2	223.5	312	7 592	风孔开启大小及风孔风量的控制困难	较差	小于 6 000 m	较难
3	4 275.75	327.2	7 008	较易	较好	长度不限	较易

由表 10 可知: 1) 方案 1 的特点是采用合流型通风井排出式通风,平行导洞作为人员疏散及救援的通道。该方案的优点是通风方案较成熟,通风网络稳定性好,通风控制及管理维护比较容易;但是其斜井主要作用为运营通风,断面较大,导致初期投资和运营费用均较高。

2)方案2的特点是将新鲜空气通过平行导洞和横通道压入主洞,分段通风、排烟,平行导洞同时作为人员疏散及救援的通道。该方案优点是可以取消斜井,大大降低土建工程投资。但是缺点是风孔开启大小及风孔风量的控制困难,通风网络的稳定性较差[7-8];且火灾工况时洞内自然风对通风网络影响较大,有一定的安全隐患,通风后期的管理维护较难;该方案只能分2段排烟,只适用于6 000 m以下的隧道,不适用于超过6 000 m的隧道。

3)方案3的特点是运营工况以射流风机纵向通风为主,斜井只需要考虑排烟风量,平行导洞作为人员疏散及救援的通道。其优点是主洞射流风机纵向通风方式成熟,斜井的断面较方案1可以减小一半,土建费用投资减少,通风网络稳定性好,通风控制及管理维护比较容易,轴流风机只需要在火灾工况开启,运营电费最省、安全性最高。

通过比选,扎尕梁隧道通风方案3土建费用适中,机电设备初期投资较低,后期运营电费最少,通风控制及管理维护容易,网络稳定性好,因此将其作为推荐方案。本项目由于地形条件所限,又处于自然环境保护核心区,造成斜井过长,前期土建费用较大,如果其他类似隧道地形条件允许,可缩短斜井长度,推荐方案的优势将更加明显。

5 结论与建议

本文针对扎尕梁特长公路隧道的特点,提出3种通风方案,并通过方案比选,推荐射流风机纵向通风+斜井分段排烟为最优方案。推荐通风方案的特点为:利用射流风机运营通风,利用排烟井分段排烟,利用平行导洞疏散救援各司其职。该研究主要解决了以下3个问题。

首先,采用纵向通风,避免网络通风控制复杂、网络稳定性差带来的安全隐患;其次,利用排烟井分段排烟,可根据排烟区段要求增设排烟井,不受隧道长度的影响,解决了平导压入式排烟方式只能分2段排烟(只适合6 000 m以下隧道)的问题;最后,利用平行导洞疏散救援,解决了单洞隧道疏散救援难的问题。

建议此类隧道在后期运营阶段,根据实际交通量及自然风进一步研究其节能及安全疏散救援的问题。

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Comparison and Selection of Ventilation Schemes for Zhagaliang Extra-long Highway Tunnel

LI Zhipeng*
(Shanxi Transportation Research Institute, Taiyuan 030006, Shanxi, China)

Abstract: In order to select a suitable ventilation scheme for a single-tube extra-long highway tunnel with two-way traffic, as well as to solve problems in smoke exhaust and personnel evacuation in such tunnel, 3 ventilation schemes are proposed. According to the characteristics of Zhagaliang extra-long highway tunnel, the 3 ventilation schemes include confluent ventilation with exhaust shaft and longitudinal ventilation with jet fans, parallel pilot tunnel forced ventilation network, and longitudinal ventilation with jet fans and sectional smoke exhaust by inclined shaft. The ventilation schemes are compared from several aspects, i. e. civil construction cost, initial investment of mechanical and electrical equipment, electricity cost during tunnel operation, ventilation control, stability of ventilation network, applicability, management and maintenance. Finally, the most suitable ventilation scheme is selected by comparing the advantages and disadvantages of each scheme, i. e. longitudinal ventilation with jet fans and sectional smoke exhaust by inclined shaft. Under the normal operation condition of the tunnel, longitudinal ventilation with jet fans is adopted in the main tunnel, and on-demand ventilation can be realized. Smoke can be exhausted by inclined shaft in case of fire, which can solve the problem of smoke exhaust only in two sections by the parallel pilot tunnel. The parallel pilot tunnel can also be used for personnel evacuation and rescue.

Keywords: highway tunnel; single-tube two-way traffic; tunnel ventilation; sectional smoke exhaust
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扎尕梁特长公路隧道通风方案比选研究

李志鹏*
(山西省交通科学研究院, 山西 太原 030006)

摘要: 为找到一种更加适合单洞双向行车特长公路隧道的通风方案,解决此类隧道排烟困难、人员疏散逃生困难的问题,结合具体工程,针对扎尕梁特长公路隧道的特点,提出合流型通风井排出式+射流风机纵向通风、平导压入式网络通风以及射流风机纵向通风+斜井分段排烟 3 种通风方案,从土建费用、机电设备初期投资、运营电费、通风控制、通风网络稳定性、通风方案的适用性以及管理维护几个方面对各个通风方案进行比选,通过比较各个方案的优点和缺点,最终给出推荐方案: 射流风机纵向通风+斜井分段排烟方案。隧道正常运营工况下,主洞采用全射流纵向通风,实现按需通风;火灾工况下利用排烟斜井进行排烟,解决平导排烟只能分 2 段排烟的问题;利用平行导洞进行人员的疏散逃生和救援,解决人员疏散逃生问题。

关键词: 公路隧道; 单洞双向行车; 隧道通风; 分段排烟

0 Introduction

At present, with the increasing number of highway tunnels in China, the proportion of extra-long single-tube highway tunnel with two-way traffic is also increasing. Compared with double-tube and one-way traffic tunnels, the probability of fire in single-tube two-way traffic tunnel is about 40% higher, according to the relevant statistical analysis[1].

Transverse or semi-transverse ventilation is used in most extra-long single-tube highway tunnels with two-way traffic in foreign countries. Transverse and semi-

* Corresponding author. E-mail: 52968861@ qq. com

transverse ventilation is the best choice for tunnel ventilation and smoke exhaust. However, it involves high initial investment, inconvenient maintenance and high operating costs. This type of ventilation is seldom adopted in newly constructed tunnels.

In China, the parallel pilot tunnel forced ventilation network is the main ventilation mode in such tunnels. Liu et al. [2] for the first time applied the semi-transverse parallel pilot tunnel forced ventilation system to the Erlangshan Tunnel (4 176 m). Zeng and Li[3], Zeng and He[4] optimized the scheme for the Zhegushan Tunnel (4 448 m). Jin and Li[5] analyzed the ventilation scheme of the Xuefengshan Tunnel by using the solution program for tunnel ventilation network. Peng et al. [6] proposed a detailed smoke exhaust and evacuation plan for pedestrians and vehicles in the Erlangshan Tunnel, based on the principle of separate evacuation of personnel and vehicles. Yang[7] studied the stability of air flow in the parallel pilot tunnel forced ventilation network in the Baizhishan Tunnel (6 710 m) by means of theoretical analysis, numerical simulation and network analysis. Yan et al. [8] investigated the influence of the number of opened transverse passages on the ventilation network in the Balangshan Tunnel (7 954 m). Jiang[9] studied the fire ventilation and smoke exhaust control strategy for a single-tube two-way highway tunnel. Wang et al. [10], Yan[11] investigated the disaster prevention and ventilation energy-saving technologies for such tunnels in high altitude areas. Chen[12], Qu[13], and Chen[14] studied the problems related to evacuation and rescue in case of fire in such tunnels. According to *Guidelines for Design of Ventilation of Highway Tunnel* issued in Jul. 2014, the maximum travel distance of smoke should not exceed 3 000 m in a single-tube two-way traffic tunnel with longitudinal smoke exhaust[15-16]. In such scheme, smoke can only be exhausted in two sections, which is only suitable for tunnels with a length no more than 6 000 m, but not applicable for tunnels longer than 6 000 m.

With more operation experiences accumulated for single-tube two-way extra-long tunnels, it is found that there are some problems related to parallel pilot tunnel forced ventilation network, such as complicated ventilation control, poor stability of ventilation network[7-8], and limited applicability of ventilation scheme. These problems have brought some hidden dangers to the safe operation of tunnel. Whether there is a better ventilation scheme for such tunnels, so that a balance between the tunnel construction and operation costs and the safety of personnel can be achieved, has become a problem that designers must study carefully.

1 Project overview

The ZYZCB-2 section from Zhouqu Lijie-Yonghe highway project in Sichuan Province starts at K99+929 and ends at K156+420, with a total length of 56.491 km. The Zhagaliang Tunnel is the controlling project of this section, which is located in Zhagaliang, Boyu Township, Zhouqu County. The tunnel starts at K123+066, and ends at K128+848, with a total length of 5 782 m, and the maximum buried depth of about 965 m. The slope is 4 705 m long, with a gradient of 1.9% toward the tunnel starting point and the design elevation of 2 463.437 m. The slope is 1 640 m long, with a gradient of −0.5% toward the tunnel ending point, and the design elevation of 2 535.762 m. The gradient change point is located at K127+675.

According to the predicted traffic volume in *Feasibility study report of Zhouqu Lijie-Yonghe highway project in Sichuan*, the short-term and long-term traffic volumes of the Zhagaliang Tunnel are shown in Table 1. The composition and proportion of various vehicle types are shown in Table 2.

Table 1　Traffic volume in Zhagaliang Tunnel

Road section	2025		2032	
	Daily traffic volume in standard passenger car/(pcu/d)	Peak hour traffic volume/(veh/h)	Daily traffic volume standard passenger car/(pcu/d)	Peak hour traffic volume/(veh/h)
Qugaona-Yonghe	1 181	110	1 758	164

Table 2　Composition and proportions of various vehicle types　%

Year	Small cargo	Medium truck	Heavy truck	Trailer	Car	Large and medium buses
2025	20.59	16.18	13.98	1.96	27.45	19.85
2032	20.39	17.78	14.54	2.26	26.68	18.35

The main technical parameters of the Zhagaliang Tunnel are as follows:

(1) Road grade: Grade Ⅲ;

(2) Traffic mode: Two-way two-lane traffic;

(3) Designed speed: 40 km/h;

(4) Non-uniformity coefficient of traffic volume in two directions: 0.52;

(5) Designed peak hour traffic coefficient: 0.12;

(6) Tunnel cross-section: Separate double tubes, cross-sectional area of 57.85 m^2, circumference of 19.29 m;

(7) Controlling wind speed: Tunnel wind speed ≤ 10 m/s.

2 Calculation of air demand

For determination of air demand, diluted smoke, dust and CO should be calculated corresponding to a driving speed of 40 km/h, 30 km/h, 20 km/h and 10 km/h, respectively. The air demand under traffic jam, ventilation and fire conditions should also be calculated. The larger air demand is taken as the design air demand, and the length of traffic jam section is taken as 1 000 m per lane.

2.1 Baseline emission of diluted smoke and dust

In 2000, the baseline emission of smoke and dust from vehicle exhaust was 2.0 $m^3/(veh \cdot km)$. The baseline emission of smoke and dust in the Zhagaliang Tunnel for the short-term design (to 2025) is $2\times(1-0.02)^{25}$, and the baseline emission of smoke and dust for the long-term design (to 2032) is $2\times(1-0.02)^{30}$.

2.2 Baseline emissions of diluted CO

Under the normal traffic condition, the baseline emission of CO in harmful gases from vehicle exhaust in 2000 was taken as 0.007 $m^3/(veh \cdot km)$.

Considering the idle speed of vehicles in traffic congestion, the baseline emission of CO from vehicle exhaust in 2000 should be 0.015 $m^3/(veh \cdot km)$, and the length of the traffic jam section should not be greater than 1 000 m.

In this project, the short-term baseline emission of CO is $0.007\times(1-0.02)^{25}$ in 2025, and the long-term baseline emission is $0.007\times(1-0.02)^{30}$ in 2032.

2.3 The air demand for tunnel ventilation

The air demand for tunnel ventilation should be calculated according to the following formula:

$$Q_{req(ac)} = \frac{A_r \cdot l \cdot n_s}{3\ 600}$$

where $Q_{req(ac)}$ is air demand for tunnel ventilation (m^3/s); A_r is clearance area of the tunnel (m^2); l is the length of tunnel (m); and n_s is minimum ventilation frequency in the tunnel.

2.4 The air demand under fire

The air demand under fire is calculated according to the following formula:

$$Q_{req(f)} = v_f \cdot A_r$$

where $Q_{req(f)}$ is air demand under fire (m^3/s); A_r is clearance area of the tunnel (m^2); and v_f is control wind speed under fire (m/s).

2.5 Calculation results of air demand

Through calculation, the air demand corresponding to the short-term and long-term design for the Zhailiang Tunnel is shown in Table 3. It can be seen that the control condition for both the short-term and long-term design is the diluted odor condition (i.e. ventilation condition). Therefore, once-through design and implementation is applied for the ventilation system according to the air demand of diluted odor.

Table 3 Air demand for different control indicators in the short and long term m^3/s

Design condition	2025		2032	
	CO	Smoke and dust	CO	Smoke and dust
40 km/h	74.12	78.32	76.13	83.96
30 km/h	63.47	47.74	67.68	53.08
20 km/h (traffic jam)	97.54	55.28	101.51	61.52
10 km/h (traffic jam)	68.35	58.79	70.04	64.67
Diluted odor	372.17		372.17	
Fire condition	173.55		173.55	

3 Ventilation calculation

In the ventilation system, the air volume and pressure provided by fans and traffic ventilation force should meet the requirements of air demand and be able to overcome the ventilation resistance.

(1) The natural ventilation force in the tunnel: The natural ventilation force is considered as the ventilation resistance of the tunnel, and the wind speed in the tunnel caused by natural wind is 3.0 m/s.

(2) The traffic ventilation force in the tunnel: In this project, the tunnel is a two-way traffic tunnel. The traffic ventilation force is taken into account as the resistance, and calculated separately according to the working conditions with various driving speeds.

(3) The friction resistance and duct loss during ventilation: The values are selected according to actual tunnel parameters.

(4) The influence of fire-heating air pressure on smoke exhaust is considered in case of fire.

(5) Increased wind pressure from jet fans: When full jet longitudinal ventilation is adopted, the increased air

pressure is balanced by the natural ventilation force, the traffic ventilation force and the tunnel ventilation resistance under the condition of stable air flow in the tunnel.

4 Ventilation scheme

4.1 Scheme 1: Confluent ventilation with shaft exhaust and longitudinal ventilation by jet fans

According to the calculation results in Table 3, the long-term and short-term air demand of the Zhagaliang Tunnel is determined by the air demand of diluted odor. Because the control air demand of the Zhagaliang Tunnel is 372.17 m^3/s for diluted odor in the short and long term, 372.17 m^3/s is taken as the design air demand, and once-through design and implementation is applied for the ventilation system. By calculation, the longitudinal ventilation of full jet fans can meet the ventilation requirements under the normal working condition, and 32 jet fans are needed in the Zhagaliang Tunnel. Considering that the maximum travel distance of fire smoke in the tunnel should not be greater than 3 000 m, a ventilation shaft should be set up.

The Zhagaliang Tunnel is constructed in massive mountain with complex terrain and large buried depth. The intersection of the ventilation shaft and the main tunnel can only be selected within 218 m (K125+848 ~ K126+066) at the middle tunnel section. The overburden depth of the tunnel ranges from 881.361 m to 933.820 m. If the shaft is set up, its depth is too large, the construction is difficult, and there is no temporary road. The condition is unfavorable no matter from the consideration of the construction safety or the project cost. Moreover, the project is located in the core area of natural environmental protection and the construction formalities cannot be gone through. Therefore, the shaft scheme is abandoned. If an inclined shaft is set up, the length of inclined shaft is slightly longer, the construction is less difficult, and temporary roads are available. Therefore, in consideration of topography, geology, geometric alignment, cost and other factors of the Zhagaliang Tunnel, an inclined ventilation shaft is set up at K126+000, and the tunnel is divided into two sections with a length of 2 934 m and 2 848 m, respectively, to meet the requirements of smoke exhaust in the tunnel in case of fire.

In the ventilation scheme 1 for the Zhagaliang Tunnel, the inclined shaft is used for ventilation in the normal working condition and smoke exhaust in case of fire. Therefore, a combination of confluent ventilation with inclined exhaust shaft and longitudinal ventilation with jet fans is adopted. The tunnel is divided into two sections for ventilation. In order to meet the requirements for personnel evacuation and rescue, a parallel pilot tunnel is constructed on the north side of the main tunnel, and transverse passages with spacing not exceeding 500 m are set up. The plan view of the ventilation scheme is shown in Fig. 1.

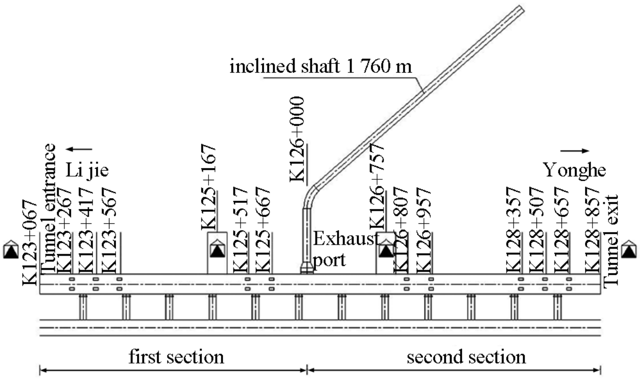

Fig. 1　Plan view of ventilation scheme 1 for Zhagaliang Tunnel

The inclined shaft has a length of 1 760 m, a gradient of 12%, and a clearance area of 27.98 m^2. The axial-flow fan room is constructed above ground. The parameters of inclined shaft and air duct are shown in Table 4.

Table 4　Parameters of inclined shaft parameters and air duct for Zhagaliang Tunnel (Scheme 1)

Type of shaft	Location of exhaust shaft	Length of inclined shaft/m	Gradient of inclined shaft/%	Clearance area of inclined shaft/m^2	Equivalent diameter of inclined shaft/m	Length of connecting air duct at the bottom of inclined shaft/m	Type of fan room
Exhaust shaft	K126+000	1 760	12	27.98	5.78	55	On ground

Bi-directional jet fans with a diameter of 1 120 mm and a stand-alone capacity of 30 kW are selected. The axial-flow fans with large air volume, low air pressure and adjustable static blades are used as the feed and exhaust fans.

The capacity of axial-flow fan should be determined based on the characteristics of the wind pressure and the air volume of the fan. The axial-flow fan shall be economical and feasible, and some redundancy should be considered. By calculation, the total installed capacity of the axial-flow fan is 827.3 kW, and three 280 kW axial-flow fans are selected. At the same time, 20 additional jet fans are needed to regulate the pressure in the main tunnel. When a fire occurs in a tunnel, in order to ensure that the critical wind speed is 3 m/s, 16 jet fans are set up to provide the thrust force by jet fans without activating the axial-flow fans in case of fire. Finally, the fan configuration for the entire ventilation system in the tunnel is obtained, as shown in Table 5.

Table 5 Fan configuration for Zhagaliang Tunnel (Scheme 1)

Type	position	Power/kW	Number of fans	Power subtotal/kW	Total power/kW
Jet fan	Section 1	30	10	600	1 440
	Section 2	30	10		
Axial-flow fan	Inclined shaft	280	3	840	

4.2 Scheme 2: Parallel pilot tunnel forced ventilation network

In this scheme, the parallel pilot tunnel on the north side of the main tunnel is utilized for ventilation and smoke exhaust. There is a fan room at each end of the pilot tunnel, equipped with a 220 kW axial-flow fan. There are 2 030 kW pressure-regulating jet fans in the main tunnel. Under the normal working condition, the fresh air outside the tunnel is evenly fed into the main tunnel through the parallel pilot tunnel and the transverse passages. The wind flow in the main tunnel is divided into two directions at the transverse passage #6 in the middle part, where the air is supplied toward the tunnel entrance and exit, respectively.

In case of fire, the main tunnel acts as a smoke exhaust channel, and the smoke exhaust mode is sectional smoke exhaust. The smoke travel distance in the tunnel is 2 900 m and 2 849 m, which can meet the requirements of the design code. Personnel evacuation is carried out through the parallel pilot tunnel. The axial-flow fans are adjusted to small air volume. At the beginning of the evacuation phase, the air pressure in the transverse passages is positive. When the evacuation is completed, the fans are adjusted to high air volume in the smoke exhaust stage. Firefighters can enter the tunnel from the entrance or exit of the main tunnel.

In case of accidents, rescue vehicles can reach the accident site through the parallel pilot tunnel. Rapid treatment can be carried out to avoid people from staying in the tunnel for too long. The sketch of the ventilation scheme is shown in Fig. 2.

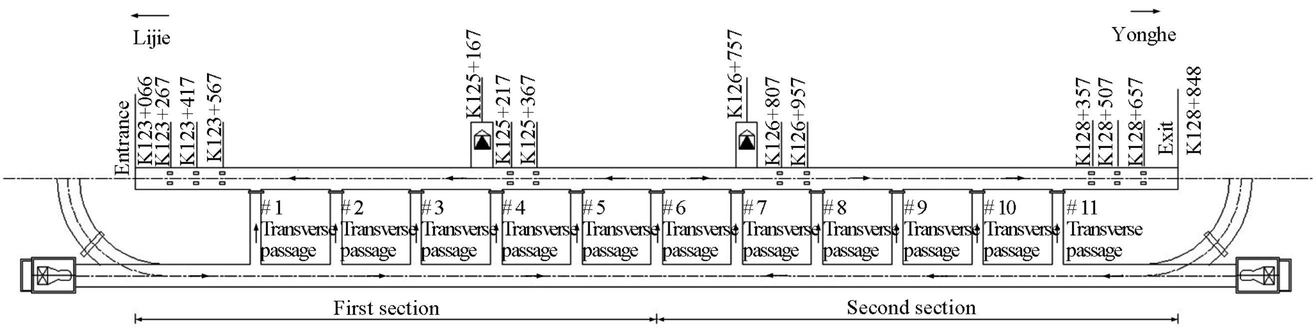

Fig. 2 Schematic diagram of ventilation scheme 2 for Zhagaliang Tunnel

The fan configuration of Scheme 2 is shown in Table 6.

Table 6 Fan configuration in the Zhagaliang tunnel (Scheme 2)

Type	position	Power/kW	Number of fans	Power subtotal/kW	Total power/kW
Jet fan	Section 1	30	10	600	1 040
	Section 2	30	10		
Axial-flow fan	Parallel pilot tunnel	220	2	440	

4.3 Scheme 3: Longitudinal ventilation with jet fans and sectional smoke exhaust by inclined shaft

Longitudinal ventilation with jet fans is adopted for the main tunnel under the normal working condition, and the inclined shaft is used for smoke exhaust in case of fire. The parallel pilot tunnel is used for personnel evacuation and rescue. The sketch of ventilation Scheme 3 is shown in Fig. 3.

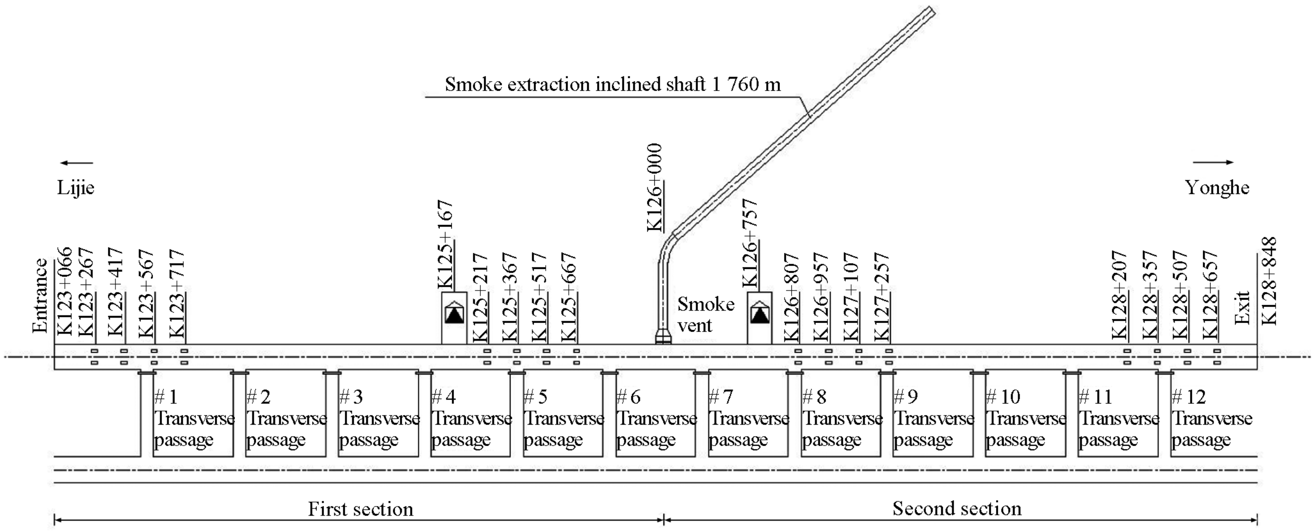

Fig. 3　Sketch of the ventilation Scheme 3 for the Zhagaliang Tunnel

Under the normal working condition, 32 jet fans are used to supply fresh air in the tunnel. In case of fire, the inclined shaft is used for sectional smoke exhaust so that the maximum travel distance of smoke in the tunnel does not exceed 3 000 m. The parallel pilot tunnel can meet the requirements of personnel evacuation and rescue.

In this scheme, the inclined shaft has a length of 1 760 m, a gradient of 12%, and a clearance area of 13. 35 m^2. The axial-flow fan room is constructed above ground. The parameters of inclined shaft and air duct are shown in Table 7.

Table 7　Parameters of inclined shaft parameters and air duct for Zhagaliang Tunnel (Scheme 3)

Type of shaft	Location of exhaust shaft	Length of inclined shaft/m	Gradient of inclined shaft/%	Clearance area of inclined shaft/m^2	Equivalent diameter of inclined shaft/m	Length of connecting air duct at the bottom of inclined shaft/m	Type of fan room
Smoke exhaust shaft	K126+000	1 760	12	13. 35	3. 6	55	On ground

By calculation, the total installed capacity of the axial-flow fans is 327. 4 kW. Therefore, two 180 kW axial-flow fans are selected. At the same time, 16 additional jet fans are needed to regulate the pressure in the main tunnel. Finally, the fan configuration for the ventilation system in the tunnel is obtained, as shown in Table 8.

Table 8　Fan configuration for Zhagaliang Tunnel (Scheme 3)

Type	position	Power/kW	Number of fans	Power subtotal/kW	Total power/kW
Jet fan	Section 1	30	16	960	1 320
	Section 2	30	16		
Axial-flow fan	Inclined shaft for smoke exhaust	180	2	360	

4. 4　Comparison and selection of ventilation schemes

In this section, the ventilation schemes for the Zhagaliang Tunnel are compared and selected in terms of civil construction cost, initial investment in mechanical and electrical equipment, electricity cost during operation, ventilation control, ventilation network stability, applicability of ventilation schemes, management and maintenance. The civil construction cost mainly includes the cost of inclined ventilation shaft (inclined shaft for smoke exhaust), connecting duct, fan room and temporary road. The comparison results are shown in Table 9.

The initial investment of mechanical and electrical equipment mainly includes the initial investment of jet fans and axial-flow fans. The electricity cost during operation is calculated for 20 years, the average operation time of fans is 10 hours per day and 365 days per year, and the electricity cost is RMB 1. 0 yuan per kilowatt hour. The ventilation schemes are compared, as shown in Table 10.

Table 9 Comparison of civil construction cost

Scheme	Inclined shaft		Connecting air duct		Fan room		Temporary road		Cost/(×10⁴ yuan)
	Length/m	Cost/(×10⁴ yuan)	Length/m	Cost/(×10⁴ yuan)	Area/m²	Cost/(×10⁴ yuan)	Length/m	Cost/(×10⁴ yuan)	
1	1 760	5 808	55	145.75	410	205	1.5	300	6 458.75
2	0	0	0	0	367	183.5	0.2	40	223.5
3	1 760	3 696	55	145.75	268	134	1.5	300	4 275.75

Table 10 Comparison and selection of ventilation schemes

Scheme	Cost of civil construction/ (×10⁴ yuan)	Initial investment of equipment/ (×10⁴ yuan)	Electricity cost for 20 years' operation/ (×10⁴ yuan)	Ventilation control	Stability of ventilation network	Applicability of ventilation scheme	Management and maintenance
1	6 458.75	452	10 512	Relatively easy	Preferably	Length is not limited	Relatively easy
2	223.5	312	7 592	Difficult to control the opening size and air volume of the air vent	Poor	Less than 6 000 m	More difficult
3	4 275.75	327.2	7 008	Relatively easy	Preferably	Length is not limited	Relatively easy

As can be seen from Table 10, Scheme 1 adopts confluent ventilation with exhaust shaft and the parallel pilot tunnel as the evacuation and rescue channel. The advantages of this scheme are that the ventilation scheme is relatively mature, the ventilation network is stable, and the ventilation control, management and maintenance are relatively easy. However, the main function of inclined shaft is ventilation during operation. It has a large cross section, which results in higher initial investment and operation cost.

In Scheme 2, fresh air is forced into the main tunnel through the parallel pilot tunnel and transverse passages, for sectional ventilation and smoke exhaust, and the parallel pilot tunnel is used as the channel for personnel evacuation and rescue at the same time. The advantage of this scheme is that no inclined shaft is needed, which greatly reduces the investment of civil construction. However, its disadvantages are that it is difficult to control the opening size and air volume of the air vent, the stability of the ventilation network is poor[7-8], and the natural wind in the tunnel in case of fire has a greater impact on the ventilation network, which has some potential safety hazards. Ventilation management and maintenance is more difficult at the later stage. For this scheme, smoke exhaust has to be carried out in two sections, which is only applicable for ventilation in tunnels with length below 6 000 m and not suitable for tunnels over 6 000 m.

Scheme 3 adopts longitudinal ventilation by jet fans under the normal working condition and only the amount of smoke exhaust needs to be considered for the inclined shaft. The parallel pilot tunnel is used as the channel for personnel evacuation and rescue. Its advantages are that the longitudinal ventilation by jet fans in the main tunnel is a mature ventilation mode, the cross-sectional area of the inclined shaft can be reduced by half compared with Scheme 1, the investment in civil construction is reduced, the stability of ventilation network is good, the ventilation control, management and maintenance are relatively easy, the axial-flow fans need to be activated only in case of fire, the electricity cost during operation is the lowest and it has the highest degree of safety.

Through comparison and selection, the ventilation Scheme 3 has moderate civil construction cost, low initial investment in mechanical and electrical equipment, lowest electricity cost for operation, easy ventilation control, management and maintenance, and good network stability. Therefore, Scheme 3 is recommended. As this project is located in the core area of natural environmental protection, the inclined shaft is long and the cost of early-stage civil construction is high, due to the limited topographic conditions. If the topographic condition allows for other similar tunnels, the length of inclined shaft can be shortened, and the advantages of the recommended scheme will be more obvious.

5 Concluding remarks

In this paper, the characteristics of Zhagaliang Extra-long Highway Tunnel are introduced, three ventilation schemes are put forward, and the recommended ventilation scheme is proved to be optimum by comparison. The recommended ventilation scheme adopts jet fans for ventilation during tunnel operation, exhaust shaft for sectional smoke exhaust, and the parallel pilot tunnel for personnel evacuation and rescue. This research mainly solves three problems.

Firstly, longitudinal ventilation is adopted to avoid the potential safety hazards caused by complex network ventilation control and poor network stability. Secondly, sectional smoke exhaust is achieved by using exhaust shaft. Additional smoke exhaust shafts can be built according to the requirements of the smoke exhaust sections, which is not affected by the tunnel length. In this way, the problem that the parallel pilot tunnel forced smoke exhaust can only be implemented in two sections (only suitable for tunnels under 6 000 m) can be solved. Finally, the problem of evacuation and rescue in single-tube tunnel is solved by using the parallel pilot tunnel for evacuation and rescue. This paper can provide some guidance and reference for the design of similar tunnels.

It is suggested that the problems related energy-saving measures, safe evacuation and rescue in such tunnels should be further studied according to the actual traffic volume and natural wind in the later stage of operation.

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