Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)
© 2019 Taylor & Francis Group, London, ISBN 978-1-138-38865-9

Civil engineering constraints on tunnel ventilation and safety

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ABSTRACT: Civil engineering, ventilation and safety design for infrastructure projects are intimately coupled subjects, which require a tight interaction and a deep mutual understanding. This is particularly relevant for complex ventilations systems and emergency exits, which can have a wide-ranging influence on the overall tunnel design. The most severe requirements are met in the case of urban tunnels, subject to space constraints, as well as for long and/or deep tunnels. An optimum design couples the different requirements and constraints in a most elegant and efficient manner to completely fulfil the scope, to guarantee all the requirements, to optimise and simplify the construction and to minimise construction and operational costs. All system's components interact in a seamless manner, allow for efficient operation and maintenance and are less prone to problems while upgrading or retrofitting the infrastructure. This paper addresses the most relevant issues, illustrates background, requirements and constraints and presents possible solutions, based on real-life examples.

1 INTRODUCTION AND OBJECTIVES

Civil engineering, ventilation and safety for infrastructure projects are intimately coupled and require a tight interaction during design and realization. Complex ventilation systems generally require larger excavation volumes or specific safety facilities. This interaction plays an important role throughout the entire life cycle of the infrastructure but is even more important for aging infrastructures. The expected life span of civil components is much larger than that of other safety system components. While the structural components are in most cases still in good condition after a few decades, most of the equipment is obsolete and needs replacement. Due to the technical and normative evolution, periodic renovations must frequently be carried out according to entirely different premises. This evolution should be accounted for from the initial design phase on, otherwise structural adaptation will be costly and could require long closures.

Costs always represent a very central aspect and must be carefully accounted for during the whole life cycle of an infrastructure. Some basic issues are reviewed in Road Tunnels Manual (PIARC 2015). Experience shows that civil engineering accounts for the largest cost share:

- Civil works account 70% to 84% of the total construction costs,
- Construction costs account for 71% to 80% of the total costs over the initial 30 years of tunnel operation.

The costs directly or indirectly related to ventilation and safety frequently represent a significant share of the cost of the civil works, particularly in case of complex ventilations or emergency exits for single-tube tunnels with high coverage. The ventilation and safety concepts are very relevant for the overall construction and life-cycle costs. They must be established and optimized and validated based on a careful interaction between civil, ventilation and safety engineering.

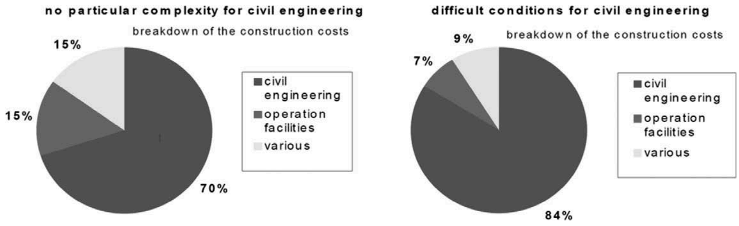

Figure 1. Breakdown of the construction costs (PIARC 2015).

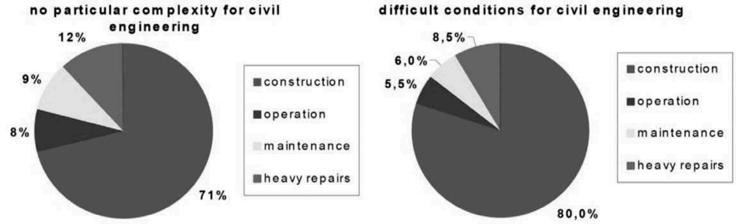

Figure 2. Breakdown of the costs during a 30-year period (PIARC 2015).

2 AERODYNAMICS AND VENTILATION

2.1 *General considerations*

Ventilation systems in underground works are designed for achieving the following goals:

- Allowing for adequate comfort and healthy conditions, in terms of temperature, air quality and visibility, during normal operation,
- Allowing adequate working conditions during maintenance works,
- Ensuring safe conditions in case of fire inside the underground infrastructure, by means of a suitable smoke-management system,
- Limiting the negative impact on air quality in the vicinity of the tunnel portals,
- Ensuring the ventilation of all accessory facilities, such as shelters, evacuation galleries, cross passages and underground technical facilities.

Ventilation and civil engineering interact at many levels. "Simple" ventilation systems (natural or longitudinal ventilations) for road and rail tunnels are generally not very demanding in terms of civil engineering. "Complex" ventilation systems, including semi-transverse and transverse ventilations, require the creation of one or two longitudinal ducts for fresh air and/or exhaust over the whole tunnel length. The cross sections needed are very substantial (typically at least 10 to 20 m^2), depending on tunnel length and on a number of geometric and traffic-related parameters. In some cases, large cross sections for ventilation result naturally from geometric constraints, as in the case of a three-lane tunnel built using a large-diameter TBM. In other cases, e.g. cut-and-cover structures subject to strict space constraints, the minimization of the cross section of the ventilation ducts represents a primary cost factor.

Early road tunnels were dominated by the requirements for normal operating conditions (air quality). While these requirements tend to diminish in time (Figure 3) in spite of increasing traffic volumes, fire ventilation requirements have increased significantly over the past decade, after the Mont Blanc tunnel event. Tunnel ventilation design is almost invariably dominated by safety requirements.

The progress achieved in fire ventilations for the road sector is slowly entering into the rail sector. It is widely recognized that long rail tunnels can experience significant longitudinal air velocities, arising particularly from barometric pressure differences and thermal effects.

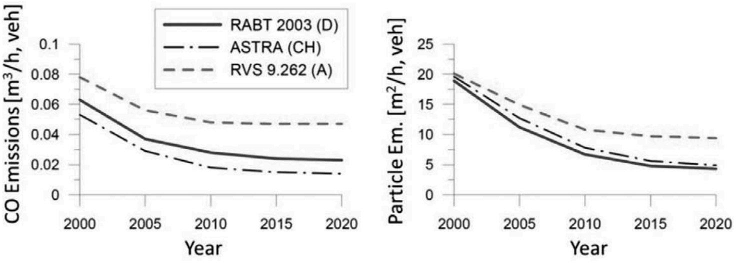

Figure 3. Evolution of specific emissions of road vehicles (Wehner & Reinke 2003).

Because of the large number of persons (up to 1000–1500) and the distance of the emergency exits (up to 500–1000 m), self-rescue times can be very substantial, up to 15–25 minutes or more (Bettelini & Rigert 2012). In many cases, acceptable conditions for self-rescue cannot be allowed without a proper ventilation system. The gap between new and existing rail tunnels in terms of ventilation is generally very large.

2.2 *Road and rail tunnels – Common issues and differences*

Common ventilation-related issues in the design of both roads and rails tunnels are:

- Missing space for jet fans (e.g. in cut-and-cover and tunnels with false ceiling),
- Missing space for smoke-extraction ducts (cut-and-cover or retrofit of existing tunnels),
- Missing space for technical rooms.

An intense interaction between civil and ventilation engineers is certainly needed and would allow, in some cases, for truly optimized solutions. While design fires for road tunnels are reasonably well defined, large uncertainties still exist for rail tunnels. Tunnels are currently designed for heat-release rates, which can vary by an order of magnitude from project to project.

2.3 *Leakages*

Leakages in exhaust systems proved to be a serious concern in long road tunnels, particularly where the ventilation was modified increasing the flowrates. Detailed experimental investigations (Bettelini 2008) showed for several tunnels in operation leakage values of the same order of the effective smoke-extraction rates at the fire location. Such ventilation systems are clearly insufficient from the safety point of view and, in such extreme cases, rehabilitation is unlikely to provide the expected results.

A specific regulation is missing in most countries, with the exception of some indications in the Swiss and Austrian national guidelines. Between 2007 and 2009 measurements conducted in 10 Swiss road tunnels (Buchmann & Gehrig 2011) allowed for a reasonable quantification of leakages (expressed in terms of effective leakage surface f*) for different tunnel types:

- Type A, new tunnels, designed and built according to current criteria: $f^* \approx 14\ mm^2/m^2$
- Type B1, retrofitted tunnels with concentrated smoke extraction and sealing: $f^* \approx 25\ mm^2/m^2$
- Type B2, retrofitted tunnels with concentrated smoke extraction and insufficient or no sealing: $f^* \approx 32\ mm^2/m^2$ (very rough estimate based on scattered measured values).

Since damper leakages typically account for only 5% to 20% of the overall exhaust duct leakage, great care must be devoted to the interaction between the ventilation and the civil engineer designing the exhaust duct. Typical issues related to leakages are:

- Contact surface between dampers and false ceiling,
- Transverse joints between lining blocks and false-ceiling sections,
- Longitudinal joints between false ceiling and tunnel lining,
- Cable passages through the false ceiling, transit points, drainage holes, fissures etc.

2.4 *Smoke recirculation*

Several types of smoke recirculation could endanger a tunnel's safety:

- Smoke recirculation from one tunnel portal to the other in case of portal smoke expulsion for double-tube configurations,
- Recirculation between tunnel portal and fresh-air inlet for tunnel or secondary ventilation (e.g. safety tunnel or ventilation of technical rooms),
- Recirculation between exhaust stack and fresh-air inlet for tunnel or secondary ventilation.

Measures for preventing this can have a significant impact on portal configuration, particularly in urban environments. Special requirements should be clarified from the beginning.

2.5 *Interaction with the environment*

The issue of smoke propagation in the neighbourhood in case of tunnel fire is frequently underestimated at design stage. This can have a significant impact on portal configuration, particularly for urban tunnels.

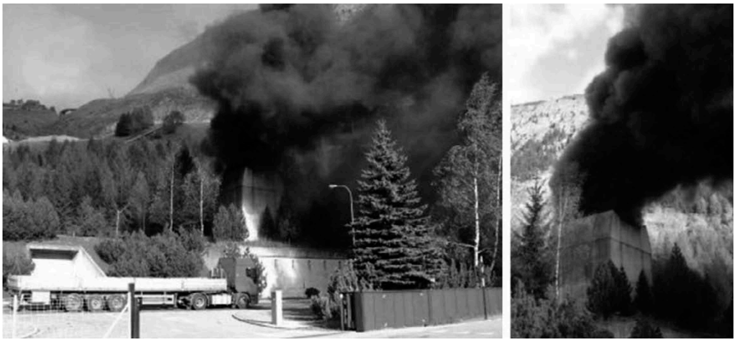

Figure 4. Smoke propagation during the 2001 fire in the Gotthard road tunnel (Source: Internet).

2.6 *Compressibility issues*

The cross-section of single-track rail tunnels can be minimized among others by using slab track instead of ballast and conductors rails instead of a conventional catenary. At high speeds, this leads to significant increases of traction power and high-amplitude pressure fluctuations, which can manifest themselves in form of reduction of aural comfort, health damages for the persons on the train, large pressure loads on the infrastructure and micro-sonic boom on the outside. Experience from a number of projects showed that these issues have very wide-ranging consequences and must be accounted for from the beginning of the design.

3 EMERGENCY EXITS AND HUMAN BEHAVIOR

For road tunnels, the directive 2004/54/EC prescribes emergency exits at least every 500 m. The requirements on the maximum distance between emergency exits in Switzerland are more differentiated and stricter (SIA 2004):

- Maximum distance of 500 m for slopes smaller than 1%,
- Linear decrease of allowable distance from 500 m to 300 m between 1% and 5%,
- Maximum distance 300 m in case of separate safety tunnel or cut-and-cover construction.

Many older tunnels were built according to significantly less stringent regulations.

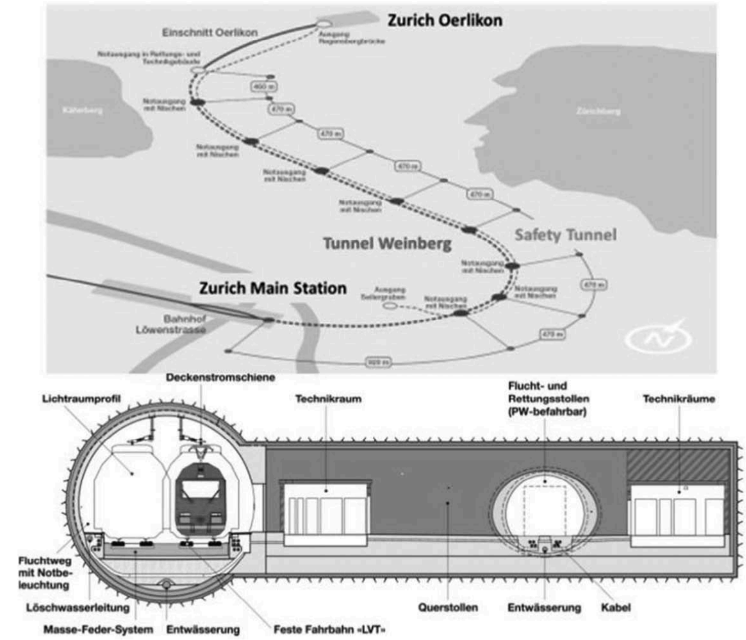

Figure 5. The Weinberg rail tunnel, in Zurich (Swiss Federal Railway).

For rail tunnels, the past requirements in terms of emergency exits were very heterogeneous. Today's minimum requirements, generally accepted in most EU countries (TSI 2014), require:

- Emergency exits to the surface at least every 1000 m,
- Cross-passages between adjacent independent tunnels at least every 500 m.

Many new tunnel projects, including all large Alpine tunnels, have cross-passages every 300 to 350 m. Similarly, many new rail projects are built together with a safety tunnel with emergency exits every 500 m or less, as e.g. in the case of the Weinberg tunnel.

Issues related to human behaviour are gaining more and more attention. According to PIARC 2008, "the design of tunnels and their operation should take into account human factors". PIARC recommended therefore a number of specific measures with partial impact on civil engineering design.

4 SAFETY CONCEPT AND INTERVENTION

Intervention concepts in road tunnels are reasonably unified and depend mainly on the tunnel system, single-tube or double-tube with cross-connections. In most cases, the details of the intervention concept do not have a significant impact on tunnel design.

In the case of rail tunnels, several entirely different intervention concepts are possible and have an important impact on tunnel design. The main concepts are:

- Intervention on rail, using fire-fighting and rescue trains (used e.g. in Switzerland, Austria),
- Intervention on rail, using conventional fire-fighting engines loaded on special wagons,
- Intervention with road vehicles, where tunnels are made accessible for road vehicles (used e.g. in Austria, Germany),
- Intervention based on mixed rail-road vehicles (used e.g. in Italy, Denmark).

These solutions are quite different in terms of kind of vehicles and training required, intervention time and strategy, investment costs and running costs.

From the point of view of civil engineering, the impact is important, e.g. in terms of:

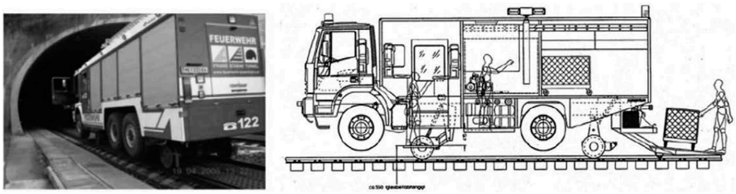

Figure 6. Examples of mixed rail-road vehicles.

- Tunnel platform and track configuration (must be fully accessible to road vehicles and connected to the road network if the corresponding solution is adopted, while conventional ballast or slab-track are acceptable for all rail-based solutions),
- Appropriate turning spaces and connections between tunnel tubes (required especially for the road-based approach),
- Tunnel ventilation (needed if conventional fire-fighting vehicles are used, but usually not mandatory for protected fire-fighting and rescue trains),
- Water supply within the tunnel tubes or at the portals is needed, depending on the approach (no need for water supply within the tunnel if fire-fighting and rescue trains are used).

Since the selected intervention strategy has a heavy impact on structural elements and equipment needed in the tunnel, the decisions on intervention have to be made in the early phase.

5 EVOLVING NEEDS

5.1 *Different time scales*

The typical serviceable lifetimes of tunnel components are 80–100–120 years for the main structure, 60–80 years for the secondary structure (false ceiling, etc.), 20–30 years for the fans, 15–20 years for the dampers, 10–25 years for further safety equipment and 10–15 years for control equipment (PIARC 2015).

It can be estimated that ventilation equipment must be replaced at least 3 to 5 times during the life cycle of an infrastructure, while the other safety-relevant components 5 to 10 times. Civil design must therefore account for modifications and evolving needs with the support of the safety specialists. Tunnels are designed and built according to the current and foreseeable needs, within the legal and technical frameworks. These can significantly evolve over the lifespan of an infrastructure. Typical issues for aging tunnels are:

- Lack of emergency exits,
- Wrong choice of ventilation system,
- Wrong ventilation design (insufficient cross-section of exhaust ducts etc.),
- Missing or inadequate control of longitudinal air velocity,
- Insufficient room for new equipment,
- Special technical issues (e.g. inadequate safety in case of large longitudinal slopes, . . .).

The San Bernardino tunnel, in the Swiss Alps, is an example of a very comprehensive tunnel renovation. The 6.6 km long single-tube tunnel was built in 1961–1967. The renovation carried out in 1998–2008 with a total cost of 240 Mio. CHF, included:

- New safety tunnel under the road plane,
- 17 emergency exits connecting the road tunnel with the safety tunnel,
- New smoke-extraction dampers every 96 m,
- New emergency niches every 250 m and new water supply with hydrants every 125 m,
- New emergency lighting and signalization of safety facilities and emergency exits,
- New water-collection system and new wall plates.

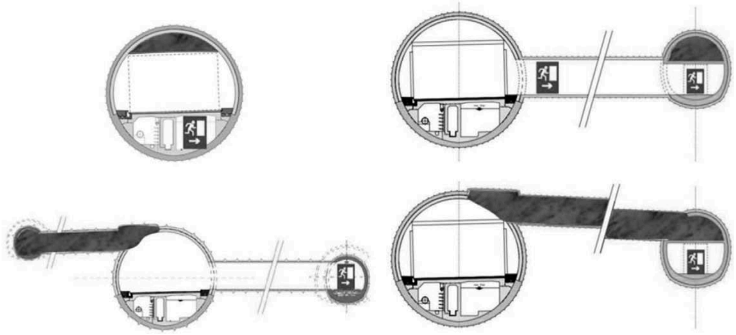

Figure 7. Some options for rehabilitating an aging road tunnel lacking emergency exits and smoke-extraction system (bidirectional traffic on two lanes, 1.5 km).

Infrastructures designed based on a rigid normative framework, satisfying the minimum requirements in a minimalistic manner, are most likely to rapidly become obsolete. A more functional approach, where normative requirements are interpreted and implemented with a global safety-based approach is much less prone to generate high additional costs.

5.2 *Standards and regulations*

Standards and regulations for ventilation and safety design of road tunnels evolved very rapidly almost worldwide after the Mont Blanc event (March 1999). Common requirements for the European countries were formalized in the directive 2004/54/EC on minimum safety requirements for tunnels, which codified the evolution of the state-of-the-art during the last decade. Important innovations were introduced from both the technical and the organizational side; the most important ones regarding the interaction between safety, ventilation and civil engineering were:

- Stricter requirements for emergency exits,
- Stricter specifications for the choice of the ventilation system,
- Significantly higher smoke-extraction rates than in the past,
- Specific requirements concerning the control of longitudinal air velocity.

All these aspects had and have severe consequences on many existing tunnels conceived according to pre-Mont Blanc requirements. Even with large national differences, the international effort for adapting existing infrastructures to this evolution was persecuted in a quite systematic manner and with very substantial investments.

The European harmonization in the rail sector resulted in the establishment of the directive 2004/49/EC on safety on the community's railways and of the Technical Specifications for Interoperability (TSI 2014). However, the modernization of the existing tunnel network is much less advanced than in the road sector and the gap, in terms of safety design, between new and existing tunnels is very large. The number of accidents in rail tunnels is significantly lower than in road tunnels and rehabilitations are considered less urgent, besides there is no general agreement on the safety standard needed in rail tunnels.

5.3 *Traffic*

Tunnel infrastructures are typically designed for 100 years but traffic forecast is in most cases very uncertain even for the next decade. Traffic volumes and composition affect not only the design of the ventilation system but also the selection of the appropriate system. This aspect is most prominent in the cases where the frequency of congestion increases significantly because of growing traffic volumes.

5.4 *New Technology: Fixed-Fire Fighting Systems*

Among the emerging technologies, Fixed-Fire Fighting Systems (FFFS) are most probably the one which could have the most lasting consequences on tunnel infrastructure and is already impacting national and international directives. NFPA 502 (2017) acknowledges its use in road tunnels, provided that the achievement of an acceptable level of safety and of the intended level of performance is demonstrated by engineering analyses and appropriate installations, inspection and maintenance schedules to maintain the level of performance intended. The application of water mist fire protection systems is regulated in NFPA 750 (2019), but a significant evolution of norms can be expected, thanks to the research activities and the experience gathered.

Fire-extinction systems were investigated particularly in the European UPTUN program, which focused on the development of cost-effective sustainable and innovative UPgrading methods for existing TUNnels (UPTUN). In the German national research projects SOLIT and after SOLIT2, the use of water mist technologies in road tunnels was analysed and optimized to evaluate the interaction with the other safety relevant measures.

FFF systems are effective in pursuing the major aim of improving conditions for escape and rescue and protecting the tunnel infrastructure. It is not possible providing general indications for the technology to be preferred for a particular situation. The interaction with tunnel ventilation, possible synergies and potential cost savings must be assessed on project-specific bases.2

6 EMERGING UNDERGROUND INFRASTRUCTURES

In urban areas, space is restricted and becomes more and more precious, while traffic congestions limit business development and create a negative impact on the life quality of the citizens. Consequently, the underground space is used not only for utilities and infrastructures but also for constructing industrial services, installations, housing or even R&D facilities. Admiraal & Cornaro 2017 provided a broad review on of the concept of underground space development investigating the issues associated with the sustainable development of urban underground space.

Representative examples of this kind of underground facilities are:

- Hagerbach Test Gallery VSH (in operation since 1970),
- WaferFab Sargans (civil works completed),
- Underground Science City Singapore (advanced feasibility studies),
- Relocation of Sha Tin Sewage Treatment Works to caverns (design phase).

Particularly, the Hagerbach Test Gallery VSH, established initially as a research and development facility for tunnel construction, provides now an underground network of galleries (total length 5 km), hosting a large variety of heterogeneous usages (restaurant, laboratory, excavation and concrete testing, fire research and fire-fighting training, conferences and social events).

The permanently increased density of the UG networks and facilities are of highly complex nature both in civil engineering and in operational aspects. This adds considerably new demands and requirements to safety and reliability. Newer underground infrastructures can be characterized as follows (Amberg & Bettelini 2012):

Figure 8. The Hagerbach Test Gallery (Source: VSH).

- Deep structures with a limited number of accesses,
- Underground working or recreational spaces, with long permanence times,
- Large number of persons, very heterogeneous groups,
- Users are not familiar with the specific underground environment,
- Mixed use, which can evolve in time.

It is interesting to notice that the emerging needs are partly contradictory:

- Pleasant environment with large, well-lit rooms,
- Flexible space organization for mixed, heterogeneous usages,
- Seamless safety system,
- High-capacity egress,
- Appropriate accesses and technical means for intervention.

In spite of widely different usages, it is possible to identify general underlying design-relevant characteristics:

- Evolution of usage with time, following interests, needs and opportunities: high-investment long-life underground infrastructures must constantly adapt to evolving needs at economically reasonable cost,
- Mixed usage with potentially conflicting usages (e.g. blasting tests and conferences) conjugated in potentially dangerous locations not accessible for unprepared visitors,
- Large person fluxes, special attention devoted to the large social events playing an important role for the economic welfare of the infrastructure and representing a major safety issue.

7 THERMAL PROTECTION OF INFRASTRUCTURE

In the interaction design process between civil engineering and fire and safety analysis, it is important to underline the objectives of structural fire resistance:

- Allowing for self- and assisted rescue under safe conditions,
- Allowing for intervention under safe conditions,
- Preventing collapse of tunnel, loss of property and minimize time for repair after a fire.

Several temperature-time curves are in use for specifying thermal protection of structural elements. The cost for thermal protection can be very high and the project-dependent choice of the curve to be applied should be carried out jointly by the safety and structural specialist. PIARC and ITA recommendations for fire protection (design criteria, materials etc.) are discussed in great detail in ITA 2017.

A representative example of comprehensive fire protection is the ventilation station Reppischtal of the Uetliberg tunnel, where a comprehensive thermal protection was required for protecting the ventilation station Reppischtal.

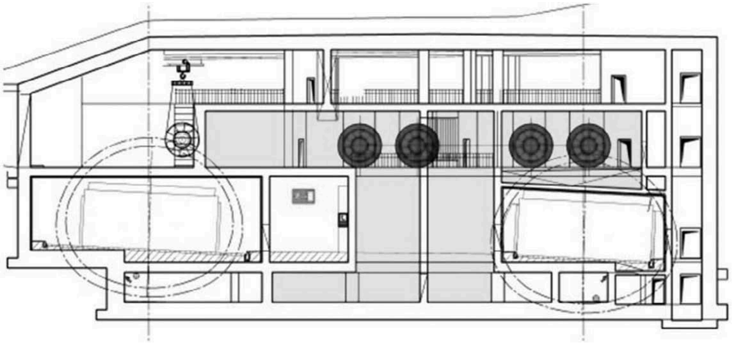

Figure 9. Cross section of the ventilation station Reppischtal of the Uetliberg Tunnel in Zurich, V=180′000 m^3 (Amberg Engineering for Canton Zurich 2009).

8 ENVIRONMENT

The environmental impact of tunnels is manifold. From the point of view of ventilation and safety, the emissions (air and water pollutants, noise, etc.) are of primary concern. Especially in urban tunnels, air pollution can be a problem at tunnel portals and should be addressed from the initial design phases. Possible measures to be investigated include:

- Ventilation towards the opposite portal,
- Ventilation system with intermediate exhaust (bidirectional traffic and low coverage),
- Portal extraction and expulsion through a sufficiently high stack,
- Portal extraction and exhaust treatment using an appropriate filtering system,
- Selecting a better-suited portal location,
- Constructive measures (tunnel prolongation with a coverage, barriers against pollutant propagation, etc).

These measures require substantial investment and, in many cases, high maintenance costs and unreasonable energy consumption. A holistic approach is required, where all economic and environmental relevant aspects of every possible solution are carefully evaluated. An intimate interaction between civil, environment and ventilation specialists is required.

9 CONCLUSION

The interactions between safety, ventilation and civil engineering are manifold and have wide-reaching consequences during design, construction and over the whole life span of an infrastructure. According to PIARC 2015, "Recent examples indicate that transverse optimisations (civil engineering - ventilation - safety evacuation) made at early project stages can contribute about 20% towards cost savings". A continuous open interaction between the specialists from the different fields is called for.

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