Major Functional Risks for Operation and Maintenance of Tunnelling Projects

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ABSTRACT

Over recent decades, the world is witnessing a rapidly increasing demand for tunnels due to their unique characteristics and potential applications such as roadway and railway transportation. However it is not unusual for any forms of risks to occur after tunnel completion and during operation and maintenance stage. This paper reviews all the key major functional risks for tunnelling projects from several case studies that have been carried out by other researchers. As a result, a more effective risk management approach can be added to the current operation and maintenance plan. And from there also, a risk contingency plan can be established or added to current risk management plan to enhance the operation and maintenance of tunnelling projects.

Keywords: *Functional risks; Operation and maintenance; Tunnelling projects; Risk management; Risk contingency plan*

1. INTRODUCTION

These days, the world is seeing a steadily expanding demand for tunnels due to their unique characteristics and potential applications. Tunnels are becoming an ever more common feature in the world's critical infrastructure. As urbanization accelerates, with rapid increasing of earth's population living in the cities, the pressure on open space to accommodate inter-urban systems will only become greater. Tunnels are artificial underground space in order to provide a capacity for particular purposes such as storage, roadway transportation, railway transportation, MRT (Mass Rapid Transit), LRT (Light Rapid Transit), underground transportation, mine development, power and water treatment plants, civil defence, space for other utilities and other activities [1]. For such variety of purposes, tunnels are differ from on-ground structures, and the design conditions vary case by case. As a result, it is difficult to rationally design and construct tunnel in all types of locations, and moreover it is not unusual for any forms of risk to occur after tunnel completion and during usage.

Tunnelling impose risks on all parties involved directly or indirectly in the project. Due to the inherent uncertainties, there might be significant cost overrun and delay risks [2]. Besides, for tunnels in urban area there is a risk of damage to a range of third party persons and property, which will be of particular concern especially where heritage designated building projects are affected. Furthermore, there is a risk that the complaint come from public when the tunnelling projects affecting them particularly in term of health and safety issues. Finally, as demonstrated by spectacular tunnel collapse and other disasters in the recent past, there is a potential for large scale of accidents happen during tunnelling operation and maintenance work.

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The prime concern in tunnel safety is the potential of serious loss of individual's life. There are a number of incidents that have focused attention on fire during operation and maintenance stage as shown in Table 1[3].

Even when fire does not result in deaths, the damage can cost millions of losses and bring towards severe disruption and consequential losses. Following the fire in 1996 and 2008 at the Channel Tunnel linking England and France, the third closure due to fire in the tunnel's history, full service was not resumed until February 2009 after repairs costing an estimated €60 million. In addition to the heavy loss of life, the estimated cost to the Italian economy of the three-year Mont Blanc Tunnel closure was €205 million, while the cost of upgrading was €206 million [3]. In short, the occurrences of accidents and other dangerous events may be not that critical in tunnel but it can result in catastrophic consequences.

This paper reviews all the key major functional risks for tunnelling projects from several case studies that have been carried out by other researchers. The review starts with identification of general risk, followed by in depth study of major tunnelling projects' accidents and the final outcome of this paper is the overview of functional risks for operation and maintenance of tunnelling projects.

Table 1: Tunnel Fire History [3]

Country	Year	Tunnel	Death/persons
Azerbaijan	1995	Baku Subway	289
Austria	1999	Tauern	12
Italy	1999	Mont-Blanc	39
Austria	2000	Kaprun	155
Switzerland	2001	St Gotthard	11

2. GENERAL RISKS IN TUNNELLING PROJECTS

Reilly and Brown [4] have specified the types of associated risks with tunnelling projects as following:

(a) The risk of damage or defects with death potential and individual damage, extensive material and economic risks and loss of credibility of individual involved

(b) The risk of failed to achieve standards and defined criteria in design, operational, maintainability and quality standards

(c) The risks of a significant delay of project delivery and execution of revenue operations

(d) The risk of significant hike of project and support costs

According to Yogaranpan [5], the general risk of tunnelling projects have been classified into four types: natural (floods, storms, earthquakes, and other natural diseases), external (economic and political), internal (strategic and improper planning) and manpower (accidents resulting in injury)

(a) Risks construction and design

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(b) The risk of operation and maintenance

(c) Other risks such as changes in the law, tax

In some other sources risks are divided into three categories [22]:

(a) Material damage to the building, machinery, devices and equipment

(b) Material damage to property of third parties

(c) Physical injury to employees or third parties

The risks of tunneling projects also refer to special problems that are occurring in the construction of underground spaces and there are difficulties for Geotechnical studies makes it check and emphasize on the creation causes of accidents in underground spaces are essentially natural or technological, and natural factors that related to geological formation, uncoordinated, groundwater conditions, and geological processes [6].

In overall, sets of tunnelling project risks are classified into two categories namely internal and external risks, which have been summarized from various sources of information as shown in Table 2.

Table 2: The risk breakdown structures internal and external resources tunnelling projects

[6, 7, 8, 9, 10, 11, and 12]

Risks from external sources	Risks from internal sources
1) Political risk	1) Contractual risk
2) The social risk	2) Investment risk
3) Economic risk	3) Employer risk
4) Legal risk	4) Management risk
5) Environmental conditions at the project site	5) Planning risk
6) Natural disasters	6) Time overrun
	7) Human risk
	8) Equipment and material resources-related risk
	9) Financial commitments and guarantees
	10) Technical risk (design and implementation)

In general, key risks that are present in business activity and that are not necessarily connected with construction, operation and maintenance of tunnels can be described as follows: economic risk, political risk, force majeure risk and technical risk. The first four risks are general risks pertaining to all types of business activity. Yet, technical risk is a specific risk for underground constructions and tunnels. According to Duddeck [13], the technical risks in the course of tunnelling can be categorized into three: risks in connection with the structure as construction-mistakes and misjudgment in constructions especially primary support and final lining of a tunnel, which render it difficult construct the tunnel efficiently and also to use it safely (construction risks), risks in connection with the contracting documents of tunnel works (contractual risks) and risks in connection with task or purpose of tunnel, or risks connected with mistakes and misjudgments, which makes it impossible to use the constructed tunnel for

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its purpose (functional risks). The functional risk is specifically present in the course of tunnel operation and maintenance [14]. Tunnel management has the aim to ensure unhindered and safe traffic flow throughout the tunnel and it is necessary to optimize all parameters of the tunnel as a whole, ranging from tunnel equipment systems, to the maintenance and monitoring of tunnel structure. The very goal of tunnel operation makes it relatively essential to manage the key risk: functional risk.

3. MAJOR TUNNELLING PROJECTS' ACCIDENTS

Mont-Blanc tunnel (Figure 1) is a bi-directional tunnel and started its operation in 1965. The tunnel connects France and Italy and the total length is 11600m. Each half of the tunnel is controlled by one operating entity, for example ATMN (Autorout et Tunnel du Mont Blanc) in France and SITMB (Societa Italiana del Traforo di Monte Bianco) in Italy. The maximum height of vault-shaped ceiling is 6m and the width is 8.5m with a cross-section of approximately 50m2 [15, 16].

Vehicle rest areas are located at every 300m and every 300m and every other rest area has a safe refuge area which is designed to provide fresh air and have a two-hour fire rating. Opposite of the rest area is a U-turn area. Safety niches are placed every 100m. They have a fire pull box and two fire extinguishers. In addition there are fire niches every 150m with water for firefighting.

Figure 1: Mont-Blanc Tunnel at France/Italy

Major fire incident occurred in Mont-Blanc Tunnel (as shown in Figure 2) during 1999, which an HGV carrying 9 tons of margarine and 12 tons of flour started to produce smoke when driving through the tunnel and stopped about 6.5km from the French portal. Shortly after stopping, flames could be seen and the fire spread to the trailer. The fire continued to spread to other vehicles at a high rate. A total of 26 vehicles (including motorcycle) on the French side and 8 HGVs on the Italian side were trapped in the smoke and later ignited. Thirty nine drivers and passengers died including a fireman who was evacuated out of an emergency shelter. Most of the victims were found dead in or near their car [17]. The cost of repair for Mont-Blanc Tunnel being estimated at approximately €206 million and the economic cost at some €205 million. In Table 3, the fire protection systems in the Mont-Blanc tunnels in 1999 (at the time of the fire) and in 2002 (after refurbishment) are described [17]. Before that, there is a minor

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fire occurred once during 1990 which involve an HGV with unknown casualties and damage but assumed to be minor.

Figure 2: The fire damage to Mont-Blanc Tunnel [16]

Table 3: The fire protection systems in Mont-Blanc Tunnel before and after the 1999 fire [17]

At time of fire (1999)	After refurbishment (2002)
Safety niches at every 100m containing a fire pull box and two fire extinguishers.	Fire-resistant stainless steel cladding fitted to walls.
Fire niches at every 150m with water supply for fire-fighting.	Concrete-lined pressurized emergency shelters at every 300m (37 in total), fitted with fire doors and connected to a safety corridor parallel to the tunnel.
Alarm and fire detection system.	
Pressurized safe refuge or emergency shelter at every 600m with two-hour fire rating (18 in total) without a safety.	A total of 116 smoke extractors at every 100m.
Outdated ventilation system with ducts underneath the roadway and limited smoke extraction capacity.	Heat sensors at both ends of the tunnel to detect overheated trucks before they enter the tunnel.
Two command and control centres at both ends with a fire fighter team at the French entrance.	Three command and control centres; the newly added central centre has a round the clock fire-fighting team.
Traffic signals every 1.2km.	More traffic lights and flashing warning signs.

The Channel Tunnel (Figure 3) forms the rail link between the UK and France which began construction in 1998 and opened in 1994. It consists of three parallel tunnel; two running tunnels, each with a single rail track, on either side of service tunnel. The tunnels are

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approximately 50 km long (37km of which is under the English Channel) The tunnel runs north-west to south-east, the northernmost tunnel is referred to as 'Running Tunnel North' (RTN) and generally handles traffic from the UK to France, with the traffic coming from France generally using 'Running Tunnel South' (RTS). The service tunnel has three main safety functions: to provide normal ventilation for the running tunnels, to provide a safe haven for passengers and crew in the event of an evacuation and to facilitate the speedy arrival of the emergency services [18].

Figure 3: The Channel Tunnel at UK/France

Three major fire incidents have occurred in the Channel Tunnel since it opened in the early 90s. The fires during 1996 and 2008 involve many heavy good vehicles (HGV) on carrier wagons and cause damage to tunnel structures as showed in Figure 4 and 5 respectively.

Figure 4: The fire damage to Channel Tunnel at UK/France

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Figure 5: The fire damage to Channel Tunnel at UK/France [18]

During 1996 fire incident in the Channel Tunnel, the structural damage is significant. Along a 50m length of tunnel, the normally 0.4 metre thick tunnel lining was reduced to a mean depth of 0.17m, with the thinnest area being 0.02m. Over a 240m long section (70m towards Britain, 170m towards France), damage to the concrete extended as far back as the first set of reinforcement bars. Superficial damage to the surface of the concrete segments was evident along a further 190m of tunnel length. In the vicinity of the fire, services were destroyed, including high-voltage cables, low-voltage cables, communications, lighting systems, traction and junction boxes over a length of 800m [18].

The 2008 fire incident in the Channel Tunnel destroying six carriages and one locomotive. Thirty-two people on board the train were led to safety down a separate service tunnel; fourteen people suffered minor injuries, including smoke inhalation, and were taken to hospital. About 650m structure of tunnel was damaged by the fire, 50% more than during the fire of 1996 [18].

The economic damage was estimated to be over twice the cost of the actual tunnel repairs. The direct repairs to the tunnel cost an estimated €60 million while the additional costs in lost business, replacement of infrastructure, materials (for example lorries, train carriages and others) together with the impact of the tunnel closure on other, unrelated business brought the economic loss alone to some €215 million.

The Tsukayama Tunnel (Figure 6) was constructed in 1967, with a total length of 1766, as a double-track railway tunnel. It is geologically in the Green Turf region, facing the Japan Sea, where Tertiary sedimentary soft rock pervades extensively. It is located at the anticlinal limb part, constituting a partially active folding zone. The overburden of the deformed section is approximately 70 m. The surrounding ground is mudstone, with a uniaxial compressive strength of 3–6 MPa. It is susceptible to slaking, and the competence factor ranges from 2 to 4. The tunnel was excavated by the bottom drift method, and the excavation and the lining were

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completed without problems. The thickness of lining is 50 cm and invert concrete was not installed [19].

Figure 6: The Tsukayama Tunnel at Japan

Shortly after completion, the tunnel deformed in such a way that both sidewalls were pushed into the tunnel space accompanied by mud-pumping at the tracks and heaving at the base. The arch crown was pushed upwards and failed in a bending and compressive manner (Figure 7). As a countermeasure against this deformation, invert concrete was installed to close the tunnel section. According to the convergence measurements between the sidewalls, the convergence had reached a maximum of 40 mm/year before the installation of the invert concrete. This was still not completely subdued by the installation of the invert concrete.

Figure 7: Compressive failure caused a longitudinal crack line in the Tsukayama Tunnel [19]

Twenty years later in 1990, however, a relatively wide area of the crown settled where compressive failure had occurred, and many shear cracks developed in a radial manner with their centre at the settled part. The possible collapse of the area was a serious concern.

In short, there are still many uncertain factors that may occur in the Tsukayama Tunnel in future although many measurements has taken due to its geological factors.

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The Rebunhama Tunnel (Figure 8) was completed in 1975 located at Japan and has a total length of 1232m. It has a double-track cross section electrified by alternating currents. It was excavated by a bottom drift method. The lining was cast-in-place concrete without reinforcement [19, 20].

Figure 8: The Rebunhama Tunnel at Japan (during inspection)

During 1999, freight train in the Rebunhama Tunnel of the Muroran Main line spotted something unusual on the tracks and applied the emergency brake. It was too late to avoid the object, however, and the train hit it and derailed. From the investigation, it was found that five pieces of concrete blocks, as large as several tens of centimeters, lay on the track and that those blocks had fallen from the tunnel arch. The site of the incident was under a rock slope of a steep sea cliff, where there was an overburden of 40 m, and the geology consisted of relatively stable Tertiary andesite or pyroclastic rock, both generally being hard. Andesitic rock block, with a size of approximately 2–3 m, was observed directly above the spalled lining, and above that relatively weak rock (Figure 9) was confirmed.

Figure 9: Lining of the Rebunhama Tunnel (after spalling) [19]

The Fukuoka Tunnel (Figure 10) was constructed in 1975; it has a total length of 8488 m. The excavation method was a bottom pilot tunnel method and the lining was cast-in place concrete without reinforcement. The geology at the site was hard green schist and the overburden was approximately 100 m [20].

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Figure 10: The Fukuoka Tunnel at Japan

On June 27, 1999, an electric power failure occurred inside the Fukuoka Tunnel along the Sanyo Shinkansen line and the Ikaria train came to a stop. The investigation indicated that a pantograph of the 12th car was broken. After a temporary treatment, the Hikari was able to run slowly to Hakata Station. It was then found that bend-tension fittings of the overhead wire of the down line were broken, and the train was put out of operation again. After repairs were made, the train was back in operation. As shown in Figure 11, a lining block making contact with the bottom face of the cold joint in the shoulder section of the arch was confirmed to have spalled. Since this was an incident which had quite a great deal of influence on society, various investigations, tests, and analyses were carried out in order to find the causes.

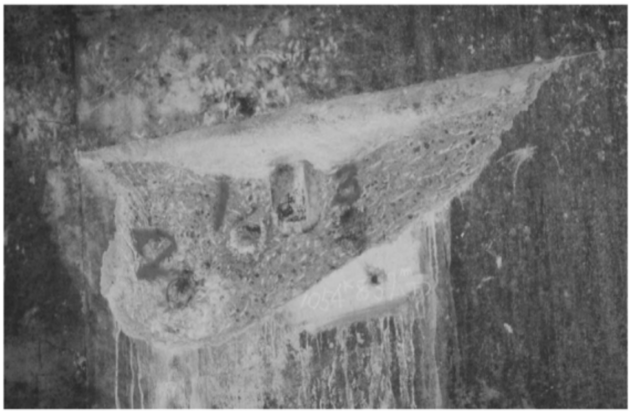

Figure 11: The Fukuoka Tunnel at Japan

Beaminster Tunnel or Horn Hill Tunnel (Figure 12) is a 105m length road tunnel on A3066 road between Beaminster and Mosterton in Dorset, England. The tunnel was constructed between during year 1830-1832; it is notable for being the first road tunnels built in Britain and the only pre-railway road tunnel in the country still can use. It was built to take a toll road underneath a steep hill to the north of Beaminster and make it easier for horse-drawn traffic to travel from the coast to the hinterland of Dorset. The tunnel underwent significant repairs in 1968 and again in 2009 [21].

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Figure 12: The Beaminster Tunnel at Dorset, England

It was shortly after a period of exceptionally heavy rainfall in July 2012 that slope failures caused landslides at Beaminster Tunnel (Figure 13) above and around the north and south portals. Part of the headwall of the north portal collapsed, and heavy debris, mud and water then crashed onto the roadway at the tunnel entrance below. Suddenly, direct northern access to Beaminster vanished, as did a primary route between Jurassic Coast World Heritage Site to the south and the town of Crewkerne- a railway station on the London-to-Exeter line- to the north. Two persons are killed in the incident.

Figure 13: Landslide occurred at the Beaminster Tunnel [21]

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4. OVERVIEW OF FUNCTIONAL RISKS FOR OPERATING AND MAINTENANCE OF TUNNELLING PROJECTS

The functional risks in tunnel operation and maintenance in the course of exploitation can be identified from three fundamental causes:

a) Hazards, act as an accidental event of any kind of environment, or within the management system;

b) Risk states, in the management system and its environment

c) Risk decisions, which are a consequence of decision-making within the organization of tunnel operation under the conditions of risk.

The information and corresponding responding communication, present in the interaction of these causes of tunnel operation and maintenance risks can represent the key sources.

Besides, the consequences of functional risks can be recognized as well from the results of several case studies that have been carried out.

From the findings, the major functional risks for tunnel operation and maintenance have been summarized into causes (sub-causes: hazards, risk states and risk decisions), sources and consequences and tabulated as following (Table 4):

Table 4: Features of functional risk in tunnel operation in qualitative term

		Tunnel operation risk	Tunnel maintenance risk
Cause	Hazards	Condition of passive safety measures; frequency and intensity of undesirable events such as traffic, fire and landslide incident	Tunnel infrastructure state, tunnel asset management
	Risk states	Active safety measures (standard operative procedures, risk mitigation plan (if applied))	Terms of quality insurance in maintenance,
	Risk decisions	From operation and maintenance plan; from operators team (subjected to changes based on conditions)	In ordinary maintenance procedures
Source		Management subjects, organizational tunnel operation structure (operator experience), environment (tunnel traffic)	Management subjects, (organizational tunnel maintenance structure)
Consequence		Endangers material, financial and economic damage (tunnel closure); influence on safety (public, users, operators and employees)	Endangers financial and economic damage; possible safety damage

From table 4, all the features of functional risk in tunnel operation in qualitative term clearly represented.

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5. CONCLUSION

It is important for tunnel operators to collect situation information necessary for establishing appropriate operational strategies as soon as possible that can be retrieved from the past incidents happened. Situation information includes type of incident, the number of vehicles involved, the number and location of trapped people, the infrastructure state and also tunnel asset management condition. And the collected information should be transmitted to the incident commanders of the first arriving teams as soon as possible through the revised plan. The operators or authorities in charge should always revise the operation and maintenance plan by including all those information by establishing more effective risk management approach through their previous experience. From there, a risk contingency plan can be established or added to existing risk management plan in order to enhance the operation and maintenance of tunnelling projects in present and future by tackling unforeseen risks.

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