IJCTA, 9(6), 2016, pp. 2957-2964 ISSN: 0974-5572

Analysis of Health and Safety Risks in Underground Excavations–Identification and Evaluation by Experts

Manuel Tender* **and João Couto****

ABSTRACT

Due to the restrictions to surface construction, underground works have a great evolution potential. The present article is part of a wider study, looking to analyse the "Health and Safety" criterion as a factor in the choice of tunneling method. Stemming from the first stage of that study, this article aims to describe the main risks in underground works using the two main excavation methods (Conventional e TBM), and estimate the magnitude of the risks identified through a set of interviews to technicians with more than 10 years of working experience. The risks were identified and grouped by class-this showed that some risks are more prominent than others depending on the method chosen. This study may be the starting point of further research; it will increase the scientific knowledge in this theme and it will provide an upgrading of industry's awareness of the magnitude of risks in underground works.

Keywords: Safety, Conventional Excavation Method, TBM, Risks.

1. INTRODUCTION

Due to the amount of new works and the financial investment for them, the international construction sector, namely in tunnelling, is developing fast. For instance, in the UK, the extremely high investments of the Crossrail 2 and the High Speed 2 are currently in the design phase. This study is part of a wider one looking into the importance of "Health and Safety" as a factor in the choice of excavation method, performing a risk assessment in both methods.

In construction, works at height, excavation and loading operations are the most dangerous and they are all present in tunnelling works. Tunnelling works' features increase their complexity and risk level (due to the high degree of geotechnical, geological and hydrological uncertainty/unpredictability; to the confined space; and to work under pressure) [1].

Tunnels are historically prone to accidents with several victims. In the Gotthard tunnel (1872-1882), 177 workers were killed in accidents, and 403 were severely injured (work with a peak of 3877 workers) [2]. The number of fatal accidents per km of tunnel has been decreasing; e.g. in the Channel Tunnel (1988-1995) the average was 0.06 fatal accidents / km.

The construction methods are divided in two groups: the Tunnel Boring Machine methods (TBM) and the Conventional Excavation Methods (CEM). The TBM uses tunnel boring machines for all of the excavation, support and lining works. There are several kinds of TBMs: no shield (for compact rock); with simple shield (close to the surface tunnels or in soft rock) or double shield (tunnels with heterogeneous

* Research Scholar, School of Engineering, University of Minho, Campus of Azurém, 4804-533 Guimarães, Portugal, *Email: manueltender@gmail.com*

** Research Supervisor, School of Engineering, University of Minho, Campus of Azurém, 4804-533 Guimarães, Portugal, *Email: jpc@civil.uminho.pt*

rock strata); for less stable soils-Slurry Shield (for thick soil) or Earth Pressure Balanced Machine (for thin soil). The CEM includes Drill and Blast and the Sequential Excavation Method, aka NATM (New Austrian Tunnelling Method). These are based on the excavation (mechanical or with explosives), ventilation of the excavation face to clear away gases, removal of excavation products to dump site, application of sprayed concrete lining, application of stabilizing devices (crankshafts, rock bolts, forepoling, etc.), and final lining.

2. METHODOLOGY FOR RISK IDENTIFICATION AND ASSESSMENT

Risk identification is particularly important since it is a way of preventing risks from being overlooked and, therefore, from giving rise to unmanageable risks. Systematic risk management has major benefits, as the early identification of major risks avoids potential problems and after-costs. To be able to identify the risks present in these works, the authors conducted a literature review. Risks were then divided into 5 groups: physical risks; chemical and biological risks; mechanical risks; biological risks; and psychosocial risks. To gauge the experts' awareness of this, it was conducted an interview with several of them, talking about the magnitude of risks in the construction of a 2 km tunnel, with normal soil and no further constraints. This was a confidential interview, conducted in person or via email. For the selection of interviewees, the following cumulative requirements were set: (1) leading role in a reputed organization; and (2) over 10 years' experience in tunnelling. The professional background of the interviewees and their years of experience in tunnelling (in brackets) are as follows: Health and Safety Executive inspector (34); Engineer in Project Owner (25); Manager of designer's company (22); Director of the Safety Department in Project Owner (24); Coordinator of the university discipline "underground works" (12); Technical Manager of explosives company (10); Tunnel Engineer in design company (22); Construction Safety Coordinator (25).

3. RESULTS AND DISCUSSION

This section describes and ranks the risks identified in the research. It also presents a discussion of the results.

3.1. Physical risks

(a) Noise-Noise is a problem in the construction field as a whole but it is worse in tunnelling because the confined space increases the reverberation of the sound field [3]. Noise stems from the cutting equipment (jumbos or rock cutting heads), ventilators, roller conveyors, concrete pumps and compressors [3]. The noise generated by the jumbo during drilling (CEM) is louder than the one generated by a TBM.

(b) High temperatures-the increase in temperature of the underground air can be due to the operation of electrical or mechanical equipment, the hydration of the concrete, or the depth increase in the tunnels. There can also be increased air humidity due to ground water presence or to the fact that the air is damp [4]. Temperatures are usually higher with CEM than with TBM [5].

(c) High pressures-Currently, tunnels tend to be excavated deeper, with higher pressures, thus increasing the risk of exposition to high pressures. The risk of work under pressure is associated to tunnel boring machines in EPB or Slurry Shield modes, due to the nature of the work required, which involves inspecting the excavation face and performing maintenance operations.

3.2. Chemical and biological risks

The air quality in the tunnel impacts the health and performance of workers [6]. Several chemical risks can be found:

(a) Dust inhalation-Excavation produces mineral dust which can have a high content of quartz, increasing the likelihood of breathable crystalline silica [7] being present. With the CEM, the excavation debris are removed by vehicles, which are prone to release dust particles, whereas with TBM the excavation products go straight from the cutting head to roller conveyors or conveyor belts. Other types of dust can also appear: dust from the sprayed concrete during the stabilization done in the CEM. The use of "alkali free" accelerators (which have a suitable pH) is recommended; otherwise, the safety conditions during transport, storing and handling decrease, as the risks of damages to the lungs and eyes increase [8].

(b) Gases inhalation-The gases inside the tunnel can have several sources:

Explosives (exclusive to the CEM) – by presence of nitrogen or carbon [9]. Despite explosives' evolution, the use of some explosives, like ANFO, brings about added risks, due to the toxicity of its vapours [10] and exposition to nitrogen peaks. This does not happen with emulsion. However, even though the fumes from pumped emulsions are low in toxic components, they can produce ammonia fumes in the presence of humidity and sprayed concrete [6].

Diesel engines – carbon monoxide or dioxide from internal combustion. The CEM uses several motorized equipment and is, therefore, more prone to this risk.

Gases in the rock mass – carbon monoxide (gas pockets); carbon dioxide (from reactions between water and rock), nitrogen oxides (from explosives), sulphur dioxide (in volcanic areas); methane (from the anaerobic decomposition of organic material; it can be present in the water); radon [5] (metamorphic rocks); hydrogen sulphide (from the decomposition of organic matter).

Welding-Propane, butane and acetylene are used in cutting and welding and can form explosive mixtures in the air.

(c) Inhalation of smoke from fires – The inhalation of smoke from fires is one of the greatest risks in tunnelling [11]. Fire can have several origins: thermal load, cables from vehicles, diesel, waste, oil leaks from machinery, compressed gas, welding and cutting. Work under pressure increases the fire risk because combustible materials burn more easily under low pressures, making it difficult to fight the fire. From the last experiences in Europe with medium to long tunnels built with TBM, it can be assumed that the risk of fire should be considered paramount [2].

(d) Contact with biological agents: contaminated soils or water or the presence of caustic or irritating substances promote contamination through inhalation/ingestion of hazardous substances. Workers are exposed to contamination if they suffer cuts or nicks, but also by simply rubbing their eyes, which may lead to leptospirosis. There is also the risk of contamination by legionella, a micro-organism [12]. This can be found in the cooling systems and closed circuit water systems (it develops rapidly in water between 25ºC and 45ºC).

3.3. Mechanical risks

(a) Run overs-The confined low visibility space creates the risk of collision between workers and machinery. Run overs are the cause of most fatal accidents in tunnels [9]. Whereas the CEM requires a lot of workers (with a greater risk of run overs) [13] and uses a lot of equipment for the removal of debris, the TBM is automated, with reduced human intervention and uses one single equipment. Also, the risk increases due to the existence of "blind spots"-areas where it is difficult to see the workers from inside the vehicles (as shown in Figure 1)-and the fact that these have a lot of inertia and are thus difficult to manoeuvre rapidly [1].

(b) Falling material from the excavation face, crown or side walls – Falling blocks from the excavation face and in the galleries, in working or circulation areas, have been identified as one of the main causes of accidents in tunnels [11]. It may happen due to the instability of the excavation face, after a fire blast and before the installation of primary support. This risk is decreased with TBM when compared to

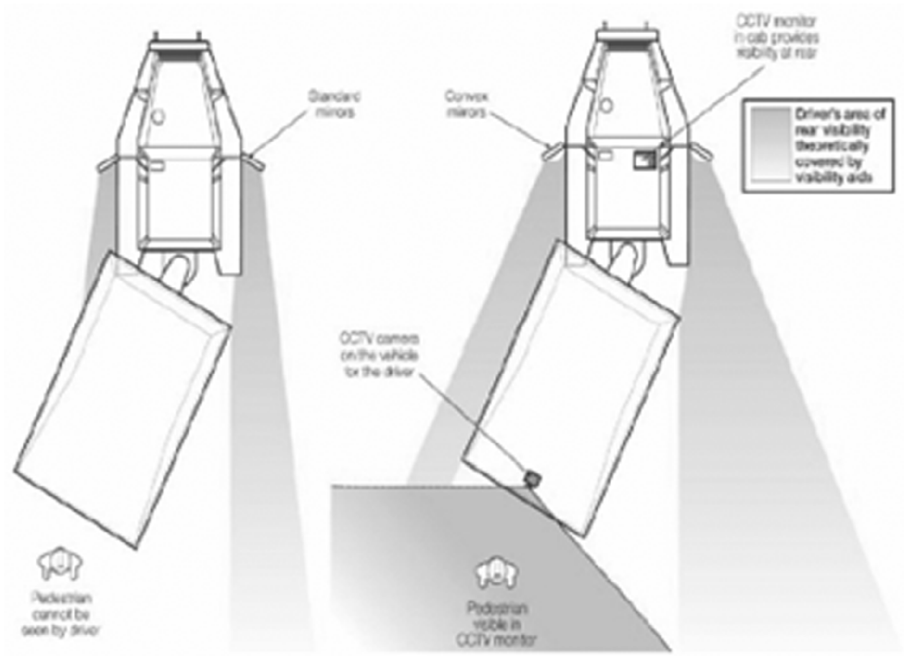

Figure 1: Dump truck blind spot

excavation using explosives. When using TBM, collapse of the excavation front may harm the public, not the workers. Also, when using TBM, the collapse is at some distance from the face, whereas with CEM it occurs close to the face [14]. There is a lower degree of probability of collapsing with TBM, provided it has been appropriately chosen and implemented, when compared to CEM [1]. Besides the collapse of the excavation face, there is also the risk of instability and falling blocks in the galleries. The CEM is more prone to this risk than the TBM, since, in the latter, the lining is conducted simultaneously with the excavation.

Rock bursting, which is hard to predict [15], is a violent decompression of the mass, resulting in damage to the lining followed by flyrock (which can result in material damage or injuries in the nearby workers) [16]. When it happens, it is more problematic at depths of over 1000m (as the transalpine experience, at a depth of 2500m, showed us) and, under similar circumstances, it is more likely with TBM than with CEM.

Exclusively with the CEM, as a consequence of blasting, there can be a risk of flyrock moving in an oblique direction (i.e., not falling in a vertical line) beyond the safety area. Its likely causes are the discontinuity of the rock mass, the inadequacy of the fire blasting plan, the overloading of the blast holes, and improper stemming.

Also with CEM, there is also the risk of sprayed concrete slabs falling from the crown or the side-walls, before the primary lining is hard enough [13]. Therefore, getting the right resistance is a key element for productivity but also for safety.

(c) Muscular and skeletal injuries-The manual handling of loads, together with repetitive movements for a long time, is one of the major problems in construction [17]. In tunnelling, the repetitive handling of tools or discs and heavy and odd-shaped material leads to frequent muscular and skeletal injuries. Adding to this, the environment is also very warm and wet, which can increase these problems [5]. With the TBM, the final lining (assembled when the TBM passes) is made up of heavy pre-cast segments (shown in Figure 2) which are hard to install, leading to risks of getting entrapped or stuck [14], namely close to the segment reception and installation area, where the operator works (usually places with low visibility). The TBM presents a further activity which increases risks connected to load handling: changing cutting disks in the excavation head.

Figure 2: Application of pre-cast segments

With CEM, the lining is done stage by stage (initial sprayed concrete and, on a second stage, which is constructed afterwards, waterproofing, reinforcement and final lining), which causes different risks. As for stabilizing methods, Swellex anchors have the higher degree of risk, due to the amount of workers involved, to the time they are exposed to the risk, and to the amount of moving materials [18].

(d) Falls and slips are a major cause of accidents [6] and are influenced by: work environment, proximity to working places, manual handling of loads (quite often of considerable weight, making them a factor which increases the risk level) [17]. When the worker cannot see where he is going, due to the load he is carrying, there is an increased risk of tripping/slipping/falling, namely when trying to overcome barriers [17] (e.g. forepoling and anchors). Especially with the CEM, the risk of falls is increased by the fact that the access ways can have rock blocks, places with water build-up and other small obstacles.

(e) Rolling / rolling-over – In both methods, there are a lot of load trucks carrying debris from the excavation face to the dump site, somewhere distanced from the excavation area. When in the mountains, the trucks have to ride on the hillside slope. This creates a high risk of equipment rolling over to lower levels (quite often in slopes of more than 40m).

(f) Untimely blast-this risk, exclusive of CEM, is connected to the handling, storing and transportation of explosives, and it is worsened when the work is in an urban area (due to the structures/infrastructures close to the surface). In terms of shape, the cartridge system has risks associated with the lack of reliability during loading, because the cartridge could get stuck in the blast holes, with the danger of non-explosion due to the lack of contact with the adjacent cartridges. In terms of detonators, electrical detonators rise the risk as they are sensible to electricity.

(g) Electrification / electrocution-In terms of infrastructures, with CEM there is a lot of energy in a short amount of time, whereas with TBM there are small amounts of energy continuously present. Power cuts, caused by deficiencies in the power grid, can have adverse effects, like transportation failure; people being locked down; light, communications, ventilation and pumping systems being cut; rises in temperature; or even the complete stop of the tunnelling boring machine [19]. The risk of electrification can increase in the CEM, due to the need of massive temporary facilities. In both methods, this risk can increase in the presence of enough water to reach the temporary power grids.

3.4. Psychosocial risks

New factors, like the emergence of new types of employment contracts, with very high workloads of physically and psychologically demanding work [20], foster the appearance of physical and psychological symptoms. Stress, for example, along with other psychosocial risks, is believed to be the cause of half of all lost workdays. A survey conducted by the main author revealed that about 82% of technicians considered that tunnelling works were more likely than building construction works to give rise to situations of stress [20].

4. RISK VALUATION AND DISCUSSION OF RESULTS

Figure 3 shows the results of the interviews and the valuation assigned to each risk in terms of occurrence of work accidents and occupational diseases. In the valuation ranges shown, the higher values correspond to a higher risk level. The survey excluded biological and psychosocial risks, due to their reduced significance.

In terms of work accidents, these are not identical in the two methods. With the CEM, the main causes of accidents are: falling blocks from the crown and side walls (high risk, due to the presence of a lot of workers in the excavation front); run overs (due to the simultaneous presence of heavy machinery and workers in the same place); and crushing/cutting (mainly during the setting up of stabilization devices). In the case of the TBM, the main causes are: fire (due to the large amount of electrical, mechanical and hydraulic pieces of the TBM); crushing/cutting (namely during the positioning of pre-cast segments and in the operations to replace the cutting disks in the excavation head); and electrification/electrocution (due to the electrical circuits in the TBM).

In terms of occupational diseases, the main causes identified with the CEM are: inhalation of rock mass dust (because the workers are close to the open excavation front. This risk is almost non-existent with the TBM); inhalation of sprayed concrete particles (due to the spraying of concrete, which is an integral part of the construction method); and high levels of noise. With the TBM, we identified: pressure changes (due to works with Earth Pressure Balanced Machines and Slurry Shields, used in works under pressure. This risk is almost non-existent with the CEM); and high levels of noise (namely during the drilling of hard rock mass).

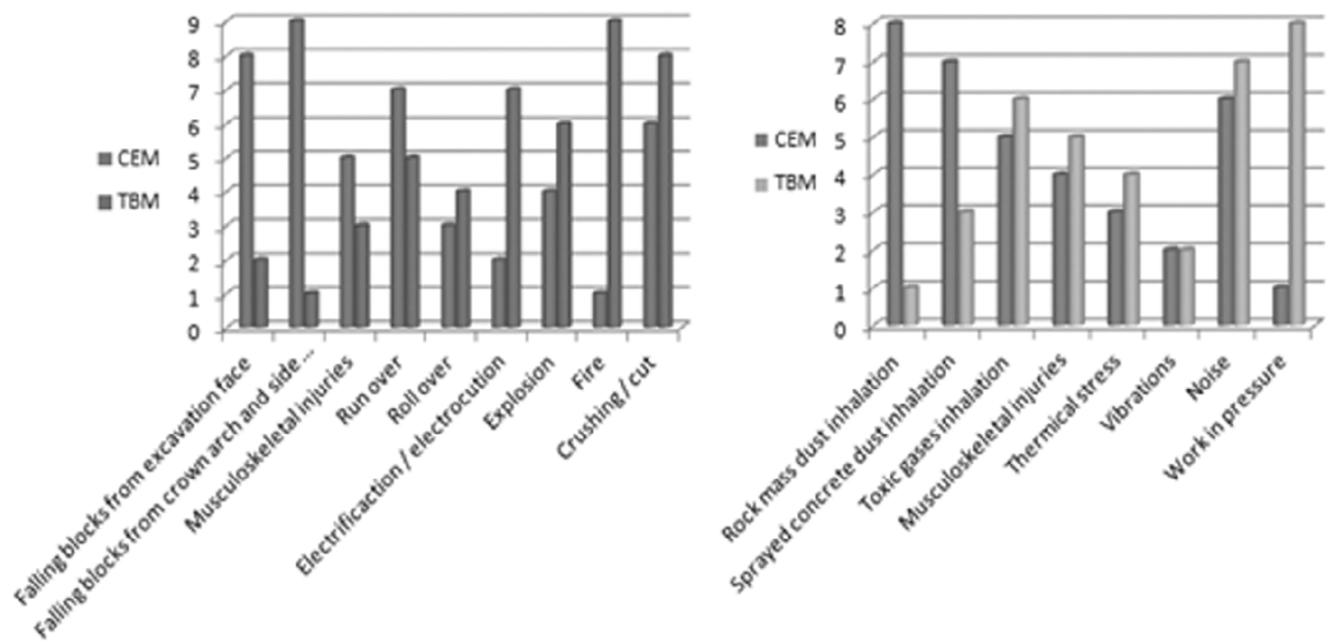

Figure 3: Main risks in CEM and TBM

5. CONCLUSIONS

After the analysis and valuation of risks, we draw the following conclusions:

- Underground works have additional risks, related to structural and occupational safety, when compared to traditional construction works;
- These risks vary greatly in type and level, depending on the method in use.

  That is, each method, due to its specificities, presents different levels of risks depending on the risk under scrutiny;
- The CEM shows risks directly linked to the amount of manpower and equipment required to operate simultaneously in a very cramped place, creating risks of workers being run over, buried, or inhaling dangerous particles;
- With the TBM, the risks are associated with the use of automated equipment, with a lot of mechanical and electrical infrastructures, which increase the risk of fires and electrification/electrocution.

The next phase of this study will involve the quantization of the risk levels, and will employ a William Fine's method for the purpose.

ACKNOWLEDGEMENTS

The authors wish to acknowledge ORICA, Mota-Engil, SIKA, and DST for the support of R&D Project "SegOS"; and Dra Alexandra Fernandes for the translation.

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