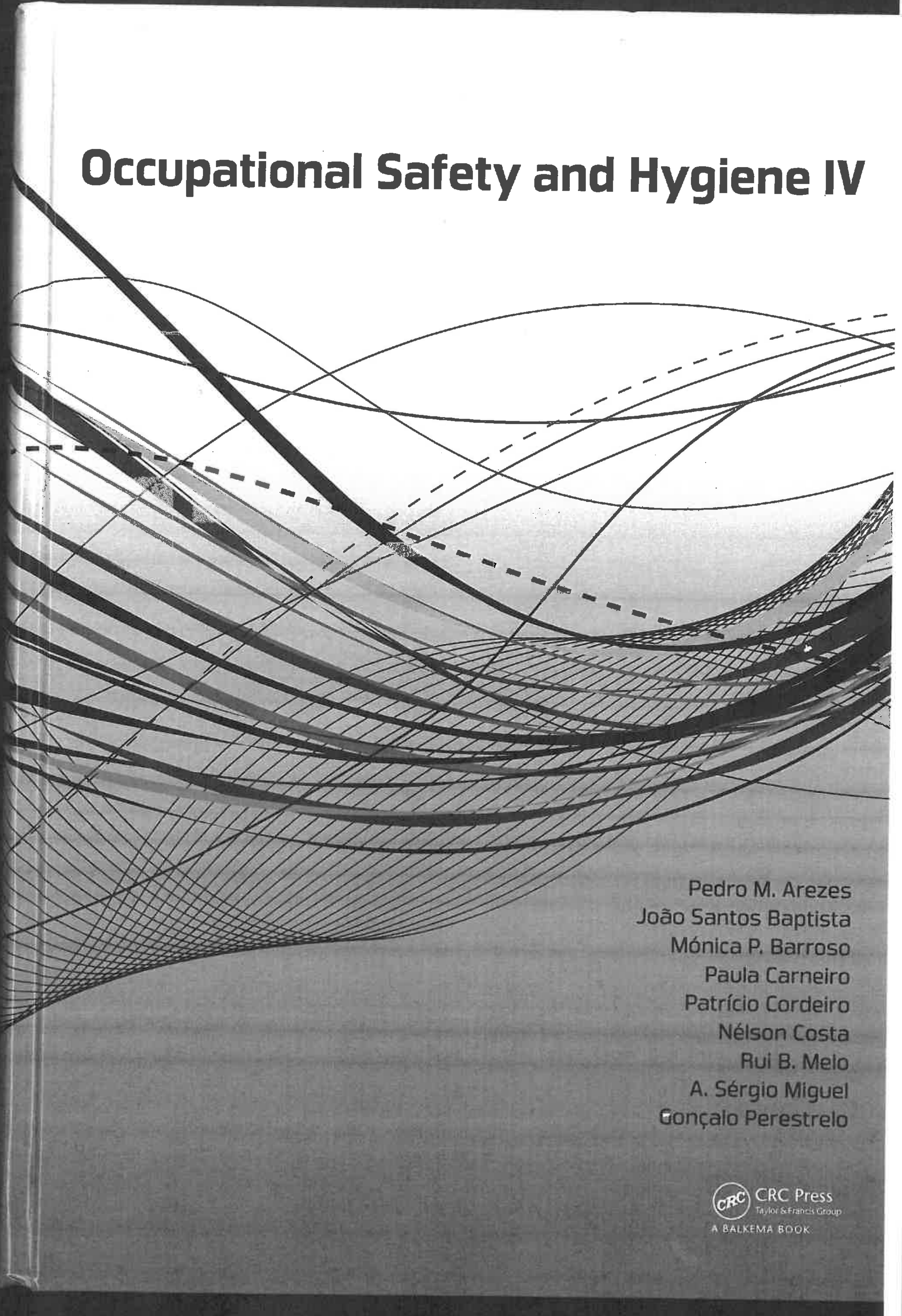

Occupational Safety and Hygiene IV

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"Safety and health" as a criterion in the choice of tunnelling method

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ABSTRACT: Risk management is of paramount importance in the success of tunnelling works and is linked to the tunnelling method and to the constraints of the works. Sequential Excavation Method (SEM) and Tunnel Boring Machine (TBM) method have been competing for years. This article, part of a wider study on the influence of the "Safety and Health" criterion in the choice of method, reviews the existing literature about the criteria usually employed to choose the tunnelling method and on the criterion "Safety and Health". This criterion is particularly important, due to the financial impacts of work accidents and occupational diseases. This article is especially useful to the scientific and technical community, since it synthesizes the relevance of each one of the choice criteria used and it shows why "Safety and Health" must be a criterion in the decision making process to choose the tunnelling method.

1 INTRODUCTION

In the beginning, the conventional tunnelling method was the only one available. With the mechanization of the last centuries, tunnel boring machines were invented—though the conventional methods never stopped being used and perfected. Both methods have been competing for several years (Singh et al., 2014) and are both frequently used, depending on the characteristics of each excavation.

Considering the impact of a work accident, it is important to analyse the framing and importance given to this aspect in the decision making process when it comes to selecting the excavation method.

2 METHODOLOGY

The literature review serves the following purposes:

- To describe the work done so far, identifying the different contributions to the field;
- To give the author's opinion about sources consulted;
- To find variables that distinguish the two methods.

For the collection of articles, we have researched the most important data bases of the field. The key terms used for the search by title were "Sequential Excavation Method", "Tunnel Boring Machine Method", "New Austrian Tunnelling Method", "Tunnelling", "Tunnelling Works".

To ensure the studied articles were credible, priority was given to primary sources, namely peer-reviewed editions. In descending order of importance, the following sources were used: 1) articles in international journals; 2) articles in national journals; 3) books published by well-known editors; 4) theses and academic essays; 5) international and national conference proceedings. Within these, priority was given to references with less then ten years and, among those, to prestigious publications with less than five years. We have also separated the theoretical from the empirical literature and priority was given to the empirical sources, so that this article can be based on real facts. As a first approach, we have read the articles' abstracts, in order to select those with the intended focus. Afterwards, the selected documents were summarized and critically evaluated, and the author strove to speculate and assess the relevance of the different perspectives given, while trying also to ascertain their origin. Finally, we conducted a synthesis of the obtained results, both converging and diverging.

The authors decided to end their search of sources when they saw that they were no longer finding new ideas and were finding a repetition of information instead. At that moment, they assume that they had sufficient knowledge of the theme to move forward.

Compared to previous literature reviews, this article aims to contribute in two ways: 1) to encompass all relevant aspects of safety and health; 2) to give a systematic review of the past, present and future of this theme; and 3) to make a first approach to the hypothesis of answers already given by other authors.

3 RESULTS AND DISCUSSION

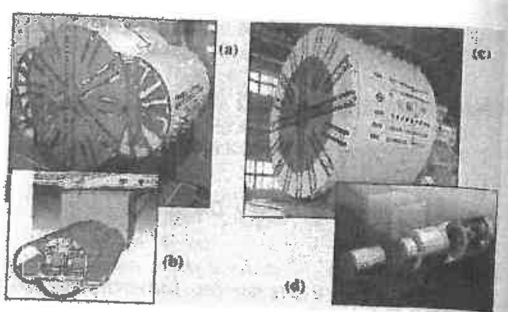
3.1 *Usual criteria for the choice of tunnelling method*

Deciding on the most suitable method for tunnelling is an old dilemma (Singh et al., 2014). Over the years, both methods have witnessed technological improvements that have increased their safety and health conditions. However, though some risks have disappeared (e.g, risks associated to gun powder with SEM), others have surfaced (e.g, with TBM, high pressure in deeper tunnels).

Note that each method has its own advantages and disadvantages in given circumstances. The main principle when choosing a method is to make sure it is able to make the tunnel in an cost-effective and safe way, showing a production peak in the most favourable conditions and being able to manage the worst conditions with bearable risks. In a given scenario, one of the methods may be excluded for being unsuitable. An example would be works where the surrounding area prevents the use of explosives, forcing the choice of a tunnel boring machine.

From the literature review we can see that several criteria are mentioned as relevant for the choice of method. The most important are the cross-section; the rock mass characteristics; the costs, length and time-frame; the working site needed; and the available equipment. These criteria are analysed below:

a. Cross-section—The geometry of the excavated area is the first major difference between the two methods. With the TBM, the section is circular with fixed dimensions (which is a major limitation to the use of this method); with SEM, the section can be variable and it is dependent only on the geological conditions. With SEM, the section can even be changed throughout the works, which can be a great advantage for complex circuits of tunnels (Jodl et al., 2011). This allows for a greater flexibility with SEM, e.g. in emergency situations due to the instability of the rock mass, when a step by step excavation is required. For this reason, the SEM has "naturally a greater flexibility" (Sousa, 2009). The SEM is, thus, better for road tunnels where the section is not circular and the width required is much greater than the height. Furthermore, in wider tunnels, we can have several work fronts, because there is more space available for the machinery.



Figures 1a,1b,1c,1d. Tunnel boring machines in the Nanboku line (Longo, 2006).

Nowadays, with the evolution of the technique, the cross-section excavated by TBM's is not longer limited to circular sections. Figures 1a and 1b show the tunnel boring machine used in the Nanboku line of Tokyo, which is the result of joining together three circular TBMs: the central machine was responsible for the central tunnel, 9,8 m in diameter, and the other machines, one in each side, increased the excavation width to 15,6 m^2 (Figures 1a and 1b). Also on that line, a machine made up of two concentric tunnelling boring machines was used, (Figures 1c and 1d). The first section of the tunnel was excavated using the larger diameter machine (D = 13,9 m) and, after the separation of the machines, the rest was excavated using the machine with the smaller diameter (D = 9,8 m). In this case, two of the typical limitations to the use of mechanized excavation (circular geometry of the excavation section and fixed diameter throughout the tunnel) were overcome.

Diameter wise, TBMs have witnessed several evolutions, allowing for larger and larger diameters, and they can, nowadays, excavate diameters of over 15 m. It is estimated that the diameters of 3 m and 10 m are the lower and upper limit for excavation with the SEM, respectively, and for tunnels between 3 and 10 m both methods may present advantages (Singh et al., 2014).

b. Rock mass characteristics—the geotechnical/geological/hydrological characteristics of the rock mass influence the choice of method. In problem areas, the SEM gives better results because the TBM has limitations in dealing with heterogeneous masses (Singh et al., 2014). With TBM, robust rock masses are an obstacle to deep penetrations, unlike with SEM, which performs better because the mass decreases the need to use stabilizing devices. When it comes to hydro-geology, the presence of water affects both methods (Singh et al., 2014).

Most future tunnels will be excavated using machines, while the SEM will remain the first choice in very complicated terrains or altered conditions (Jodl et al., 2011). This opinion can be justified by the remarkable evolution of TBMs, though still with a few limitations with regard to the type of ground, stemming from the concept of the equipment. As for the SEM, it is likely that the blasting excavation methods will remain predominant at the world level, especially outside urban areas.

c. Costs, length and time-frame—In tunnelling, like in other areas, achieving the best cost (though it is always very difficult to predict the cost of underground works due to the variables involved) (Nord, 2006) is one of the main choice criteria. Several articles mention the length of the tunnel as a key criterion for choosing the right method, from a technical and economic point of view. Analysing the advance rate data from several tunnels, it is clear to see that it varies widely, and this makes it hard to make a direct comparison between both methods. First of all, it must be stressed that the yield of both methods must take into consideration the time needed to assemble the machines to be used. Due to the long time needed to make and assemble the machine, in the TBM this aspect increases in weight if the tunnel is shorter. For longer tunnels, the delay in starting to work is compensated by the greater progress speed of the TBM. When it comes to costs, then, the two methods are opposites: high initial cost with low continuous cost (for TBM) and low initial cost with medium continuous cost (for SEM). We must also consider parameters that may cause delays. So, for SEM there is a waiting time between the blast and the end of ventilation (especially for long tunnels) that can drastically reduce the speed of excavation. As for the TBM, the excavation is partially continuous, except in areas of geological constraints, which affects both costs and deadlines (Singh et al., 2014), and that is why this method presents greater excavation speed and faster execution times. In terms of available work fronts there are also differences: With SEM, there can be a front per portal (or in intermediate points), with a duplication of fronts and the related reduction of probability of a problem occurring in both fronts at the same time; with TBM this is not so common.

Several authors mention different lengths for which one method is more profitable than the other. Up to 2000 m, the SEM has more advantages; over 3000 m, the TBM is better (Singh et al., 2014). Other references give the minimum tunnel length of 5000 m for the TBM to be competitive with the SEM (Rieker, 2015). Yet other sources mention that, for tunnel lengths of between 1500 and 4500 m, under the same circumstances, the TBM and the SEM will present similar costs (Barbosa, 2008). After comparing the total cost of tunnels made with the various construction methods, is has been show that, for tunnels under 2400 m, with varying geometry and under variable geological-geotechnical conditions, the conventional excavation methods are more cost-effective. However, there is an overlapping area where both methods can be chosen, when it comes to cost. Adding all of these quantified opinions, we can conclude that, for the same construction conditions, for tunnels under 1000–1600 m, the SEM is the most suitable, and for those over 3000 m–4500 m, the TBM is the most suitable.

d. Construction site needed—The construction site needed for each of the methods is necessarily different. For the TBM, it is necessary to have a construction site big enough to assemble the machine parts (Brox, 2013), with an initial section of 50 to 150 m. The SEM does not need this. Usually, the TBM also needs a place to store precast segments (usually equivalent to a week's production. For example, 40 advances will require 800 m^2 of storage room), before they are assembled in the excavation, plus a place for a gantry lifter for the parts. In the case of soft grounds, it may also require places for silos for recycling muds or places where the excavated debris that come out wet are left to dry out.

Regarding accesses, TBM may demand additional work, due to the load bearing capacity needed to support the transportation of parts that can weigh up to several dozens of tons (the heaviest part weighs around 50 to 100 tons). This heavy weight may demand increasing the load bearing capacity of roads or installing high capacity cranes to assemble the equipment.

e. Available machinery—The methods have opposing philosophies: The SEM is a method involving many workers and different equipments, whereas the TBM method is automated, with fewer workers involved and the use of one larger equipment. Figure 2 shows the control station of a boring head.

f. The SEM uses multiple equipments (small machinery, commercially available (Figure 3), and ready to use after purchase), with the

Figure 2. Boring head command centre (Crossrail, 2015).

Figure 3. Equipments used in SEM (author's photo).

consequent increase in labour-force (Skawina, 2013) and run-over risks (Tender et al., 2015b).

The TBM uses only one automated equipment for excavation, which requires several months for construction and assembly – 6 to 12. However, this delay is compensated by the TBM's higher yield when compared to the SEM.

3.2 *Study of the "Safety and Health" criterion*

Several authors sustain that, throughout the choice process, besides these criteria, and with a secondary character, a risk analysis must also be performed. However, said risk analysis is usually done from a structural/geotechnical point of view and does not asses risks linked to the occupational safety of the workers. This underrating of the identification of occupational risks is a gap in the decision making process concerning the choice of tunnelling method. In a situation where any of the methods could be used, the fact that this assessment is lacking could lead to the wrong choice and increased number of work accidents and occupational diseases, with a high financial and logistic impact when the work has to be halted or due to income losses.

The big differences between the two methods make it hard to compare them directly, since the tasks, equipments, and materials involved are very different. Nevertheless, with the right procedure (namely, by using the same premises, environment and constraints), we can draw some generic conclusions (Jodl et al., 2011).

The literature reviewed mentions this, stressing several essential characteristics for the differentiation of the methods. The SEM is prone to occupational diseases, due to the pollution caused by the explosives, exhaust fumes from lorries, and dust from the sprayed concrete (Tender et al., 2015a). This does not happen with the TBM, where the air quality is better because it has no smoke or diesel fumes (Jodl et al., 2011). When it comes to the stability of the excavation front, the use of TBMs is seen as safer, since it guarantees a better environment than the SEM, and it keeps the excavation stable (Skawina, 2013). The TBM method can be seen as a safer method than the SEM, with less rock mass damage and with the possibility of remote operation (Singh et al., 2014). The SEM can be problematic due to vibrations, gases, noise levels, damage to the rock mass due to the blasts, and emission of carbon oxides and nitrogen (Skawina, 2013). Statistically, both methods show similar current figures of work accidents (Jodl et al., 2011). According to HSE's experience studying the Heathrow accident—we can say that each method presents a specific set of features that induce a certain type of risk which is not present in the other method, something that we will explain in more detail further ahead (Health and Safety Executive, 1996). The same reference states that, in tunnels built between 1960 and 1970, the index of accidents with the TBM was half the one with the SEM, and that the severity index was the same for both methods. However, more recently is stated that SEM, provided that the convergence is limited, can be used safely in urban areas (Romana, 2009).

The long Norwegian tunnelling experience mentions that there are no evidence supporting the statement that one method is safer than the other (Holen, 2011). The lead author also reached the same conclusion, when he was unable to get any compiled statistical data (concerning work accidents and occupational diseases) from several tunnelling bodies, both national and international, during his MSc's Thesis production (Tender, 2014). The only exception was the Japanese Tunnelling Association, which has organized a set of statistics (although not presenting numbers about workers involved) relating to major injuries and fatal accidents (shown in Table 1) occurred in 2012 (Kikkawa, 2015), when 700 km of tunnels were under construction in the country.

First, we must stress that most accidents, near excavation face and in galleries, happen with the SEM. Using SEM, most of accidents near the excavation face can be explained by the excavation front unprotected and with manpower and equipments in a cramped space; accidents occurred far from excavation face are consistent with simultaneous presence of workers and equipment in circulation and by the final lining made weeks after the primary lining. With the TBM, accidents near excavation face are rare as there are no risk of trapping, runover or falling blocks. The temporary structures appear as the main cause of accidents, fact that can be associated with presence of huge amounts of electrical and mechanical infrastructures supporting principal machine working.

Table 1. Major injuries and fatal accidents (2008–2012) in SEM and TBM.

Factor involved/ place of accident	Excavated front (SEM)	In tunnel (SEM)	In TBM	In tunnel (TBM)
Mobile plants	17	27	3	4
Lifting plants	3	9	2	9
Other plants	1	7	0	3
Temporary structures	5	16	0	12
Materials	9	13	3	7
Environment	33	1	0	2

4 CONCLUSIONS

This study has given rise to a bibliographical research on the theme. After the analysis of the several criteria and specially of criterion "Safety and Health", we can draw the following main conclusions:

- The criteria usually employed show very marked differences between the methods.
- The "Safety and Health" criterion is usually underrated with regard to the other criteria. However, this may not be the best choice, due to the production, logistics and financial impact that a severe or deadly work accident or health disease can have.
- The non-existence of international statistical data about work accidents and diseases is a major gap that should be overrun in order to stablish a correct and deeper comparison between the two methods.

This study will be the starting point of a second phase of studies, which will analyse the subject in more detail with the aim to quantify the risks associated with each method.

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