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Risk evaluation in tunneling excavation methods

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Abstract

Risk management is of paramount importance for the success of tunneling works and it is linked to the main excavation methods used: the Conventional Excavation Method (CEM) and the Tunnel Boring Machine Method (TBM). Considering the importance of the "Safety and Health" criterion for the choice of the excavation method, the fact that this criterion is usually mostly focused on the structural component, and taking in account that there is no research showing the advantages of one of the methods over the other, this research intends to conduct a comparative risk analysis between both methods, taking into consideration the different constraints that might appear. In order for this comparison to hold true, a risk evaluation is presented, analysing 12 risks and 4 risk factors in 3 phases, so that the impact of the different variables can really be appraised. This research is made in a scenario of the construction of a 3.5 km-long tunnel in a non-urban area, with an unproblematic rock mass. The final result will be a detailed analysis of the influence of "Safety and Health" criteria, useful for both the technical and the scientific community, something that has never been done before.

Keywords: CEM, TBM, risks, health and safety, prevention.

1. Managing underground works

a. Risks

The use of the underground space is increasing because it can improve mobility, quality of life and social sustainability (Tender *et al.,* 2017a). Risk management has been implemented in these works, but usually focused on structural risk (dealing with geological and geotechnical aspects) rather than occupational risk (dealing with workers' health and safety conditions - not scientifically explored, and which is the core of this study).

Risk management is guided by the International Organization for Standardization (ISO) 31000: 2009 (which is currently being updated), supporting a four-step approach to risk: planning, implementing, monitoring, and reviewing.

Risk management is justified for 3 main reasons: 1) **it is a legal requirement;** 2) **it follows the general principles of prevention;** 3) **it decreases the number of accidents at work (AW) and occupational diseases (OD),** because it enables an early identification of potential hazards (Eskesen *et al.,* 2004), a quantification of risks, comparing them to predefined criteria (Carvalho and Melo, 2013), a timely decision on the most suitable preventive measures (Eskesen *et al.,* 2004) and turning a risk situation into sustainable competitive advantages (Azevedo *et al.,* 2014). A non-existing or incorrect risk management can lead to AW or OD. Time-wise, a serious AW usually causes an interruption of works that may have an impact on the overall execution time, as it can range from a few hours to several days, pending the gathering of all the data for the investigation. Cost-wise, it has high economic implications (Hermanus, 2007), with costs estimated (together with those of OD) in 8.5% of the project costs (European Agency for Safety and Health at Work, 2014a), with a potential to reduce the company's profit margins, affecting its competitiveness. Risk management is crucial for the success of the works, and it is linked to the construction method. This study analyses the two main excavation methods: Conventional Excavation Method (CEM) and Tunnel Boring Machine Excavation Method (TBM), thus focusing on the first two steps of ISO 31000:2009: planning and implementing.

b. Bibliographic review

Risk varies according to the method used (Tender and Couto, 2016), but few studies deal with this issue (International Tunnelling Association, 2016): Aneziris assessed 63 risks on a tunnel built using CEM (Aneziris *et al.,* 2010); Fouladgar assessed eleven risks, not specifying the method (Fouladgar *et al.,* 2012); Tender assessed risks with 10 specialists differentiating between methods (Tender and Couto, 2016). Other authors have conducted global comparisons and they state, without quantifying, that CEM has greater risk levels: *"unhealthy due to exhaust gases"*(Jodl and Resch, 2011), *"more exposed to the excavation face"* (International Tunnelling Association, 2016); or that TBM has better risk levels: *"improves conditions"* (Lamont, 2012); *"safer"* (Singh and Zoldy, 2014); *"increases safety levels"* (Fulcher *et al.*, 2015). Two recent statements sum up the relevance of the present study: *"There are no internationally accepted studies on the advantages of one or the other method in terms of safety and health"* (Fulcher *et al.*, 2015);*"There are no indications for a systematically different level of health and safety in both methods"* (International Tunnelling Association, 2016). Thus, it is impossible for stakeholders to know beforehand what impact the choice of method will have in terms of health and safety.

With the goal of filling in these scientific and technical gaps, the following questions are asked:

Q1 - Which excavation method presents higher risk levels?

Q2 - Which work phase presents higher risk levels?

Q3 - Which are the risks with intolerable levels per work phase?

Q4 - Which underground excavation method presents the biggest tendency to have conditions prone to the appearance of the risks factors identified?

Q5 - Which phase has higher levels of risk propensity, in each of the methods?

Q6 - Which are the occupational factors with intolerable levels per work phase?

2. Research methodology

a. Risk identification

Risks identification was based on the variable "Deviation" of the European Statistics of Accidents of Work, with few adaptations: electrisation/electrocution (ELEC); diesel gas inhalation (DIES); fire smoke inhalation (FIRE); rock mass and sprayed concrete dust inhalation (DUST); exposure to chemicals (CHEM); rupture (RUPT); fall of blocks and sprayed concrete fragments (BLOC); collapse (CLPS); fall of person on the same level/to a lower level (FALL); musculoskeletal problems (SMSD); run-overs (RUNO); exposure to biological substances (BIOL). Since this is a comparative study, it will not analyse risks that are only present in one of the methods (e.g., untimely blasts (CEM) and pressure differences (TBM)). In terms of risk factors, four environmental factors traditionally present in underground works were chosen: noise (NOIS), vibration (VIBR), extreme temperatures (TEMP), and stress (STRS).

b. Risk assessment

The law does not specify the methodology to be used for assessment of health and safety risks. As the qualitative methods do not present numerical results and the quantitative ones require a complex evaluation, this study uses semi-quantitative methods, recommended by several national and foreign authors to prioritize and guide the allocation of resources. The William Fine Method (WTF) was selected because it meets the 5 risk index levels recommended by the International Tunnelling Association (Eskesen *et al.*, 2004) in order to avoid risk loops (i.e. different "risks versus consequences", which, when evaluated, may end up sharing the same Risk level). The risk magnitude (Rm) value is calculated by the expression: Rm=ExPxC. The meaning of each of the factors (E, P and C) is explained below.

Exposure (E) - the frequency with which a situation that is capable of triggering an accident during the activity performed is classified. Table 1 shows the value assigned to factor E.

EXPOSURE FACTOR (E)	Value
Continuous – many times / day	10
Frequent – once / day	6
Occasional – between 1x / week and 1x / month	3
Irregular – between 1x / month and 1x / year	2
Rare – it can happen, but it has a very low frequency	1
Unlikely – it is not known whether it happens, but it is possible	0.5

Table 1
Exposure factor values
(adapted from Cabral, 2009).

Probability (P) – the possibility of occurrence of a hazardous event, with or without damage. The value attributed to the factor P is shown in Table 2.

PROBABILITY FACTOR (P)	Value
Very likely – most likely result if hazardous event occurs	10
Probable – it is likely to occur	6
Rare – of rare incidence	3
Improbable repetition – it has happened, but it is not likely to happen again	1
It never occurred – of extremely remote incidence	0.5
Practically impossible – it has never happened in many years of exposure	0.1

Table 2
Probability factor values
(adapted from Cabral, 2009).

Consequences (C) – the most probable results that the occurrence of the hazardous event would have. The value assigned to factor C is given in Table 3.

Table 3
Consequence factor values
(adapted from Cabral, 2009).

CONSEQUENCE FACTOR (C)	Value
Catastrophe - many fatalities	100
Several deaths	50
Death – fatal accident	25
Serious Injury / Permanent disability	15
Temporary incapacity	5
Light injuries	1

Table 4 shows the risk magnitudes, grading and priority of intervention (Kinney and Wiruth, 1976).

Table 4
Magnitude, risk grading and priority of
intervention (adapted from Cabral, 2009).

RISK MAGNITUDE (Rm)	GRADING	PRIORITY OF INTERVENTION
Greater than 400	Imminent	Immediate suspension of the dangerous activity. Immediate correction is necessary.
Between 200 and 400	High	Immediate correction. Task should be stopped until risk is minimized.
Between 70 and 200	Considerable	Correction needed urgently.
Between 20 and 70	Moderate	It is not urgent, but should be corrected.
Less than 20	Acceptable	Correction may be omitted.

The Rm measurement scale ranges from 0.05 (most favourable scenario) to 10,000 (most unfavourable scenario). When the value of Rm is known, the level of intervention required is identified. The values indicated in the results of this research correspond to the average of the values attributed by the respondents.

It is important to consider the threshold of tolerability, above which, after risks have been identified and the sacrifices in terms of cost, time and effort to avoid them have been assessed (Gadd *et al.*, 2004), the costs of reducing the risk would outweigh the benefits of the reduction. The WTF has predefined acceptance criteria, with the tolerability threshold set at Rm=200. For values of Rm greater than 200, it is considered that the preventive measures implemented are not enough for the task to be safely performed and, therefore, intervention is necessary.

It is crucial that the method be reliable, and that the data be obtained regardless of the instrument, the assessor or the time of the assessment. This is, however, one of the semi-quantitative (Carvalho and Melo, 2013), weaknesses, which may condition the results obtained. The WTF method is not fully validated, which might be a problem for this study. However, the study's sole goal is to establish a comparison between the risk levels in excavation methods, which means that the real support for the compared assessment (in terms of stability and reproducibility) is the panel of experts, not the WTF method per se.

Due to the lack of works in Portugal where it would have been feasible to carry out measurements to compare risk factors, the alternative was to carry out a qualitative analysis of the propensity for the occurrence of risk factors in order to understand which of the methods presented the highest propensity for the occurrence of OD, for each of the risk factors identified. The Rp index (Risk Propensity Level) was created for the propensity for each risk factor. The scale used was 0 (Low propensity), 1 (Medium propensity), and 2 (High propensity). The Rp tolerability threshold was set at 1.3. Table 5 shows the magnitude and grading of risk propensity.

Table 5
Magnitude, risk grading
and priority of intervention.

RISK PROPENSITY LEVEL (Rp)	GRADING	PRIORITY OF INTERVENTION
Between 1.3 and 2.0	High	Suspension of the activity
Between 0.7 and 1.3	Medium	Correction needed urgently
Less than 0.7	Low	Correction may be omitted

Tolerability is also a concern when it comes to the Rp level. In the same way as for Rm, it is necessary to define a criterion of tolerability for Rp. The value of Rp set as a tolerance limit is 1.3. For values higher than 1.3, it is considered that the preventive measures implemented are not enough for the task to be safely conducted and intervention is therefore necessary.

c. Tasks to consider

The tasks were divided into 3 groups: Phase 1 (1F): Excavation/muck removal; Phase 2 (2F): Primary support; Phase 3 (3F): Final lining, including application of formwork, concreting and formwork release of the final lining (CEM), and assembly of prefabricated segments (TBM). The Rm value considered for each risk was determined through the sum of the means of Rm values for the three activity groups (Eskesen *et al.*, 2004). The initial scenario considered was that of a tunnel with 3250m (length at which both methods are technically and financially viable), in a mountainous rural area, with a healthy and dry rock mass, able to be excavated using hammer or tunneling machine without shield, and without simultaneity of tasks. The respondents were given information about the preventive measures (selected by the authors as the minimum requirement of the Health and Safety Plan) already implemented in the risk assessment, since these measures interfere with risk magnitude.

d. Survey application

It would have been ideal to be able to link "probability" to the real frequency of AW or OD, and "consequence" to the number of lost days and the impact on the patient, but the lack of reliable data makes it impossible (Rodrigues *et al.*, 2015). Thus, the alternative was to conduct a survey with a panel of experts, in order to assess their ideas as to the level of each of the risks and the propensity for risk factors, in the three phases, for each of the excavation methods. The criteria for selecting the respondents were: people who worked in underground works, with a 5 years' minimum experience in the field. The survey was conducted between November 2016 and January 2017, with a group of 30 respondents: 43% represented work owners, 37% designers, 7% contractors, 10%; work oversight and health and safety coordination in the construction stage, and 3% other entities.

3. Results and discussion

Answers for each question are marked in bold (Qx implies Ax).

A1 - The excavation method presenting higher risk levels is CEM. For all risks, except for BIOL, the absolute majority of the respondents was of the opinion that CEM presents higher Rm than TBM; the figures varied depending on the risk: *"electrization/electrocution"* (63%), *"diesel gas inhalation"* (63%), *"fire smoke inhalation"* (47%), *"rock mass and sprayed concrete dust inhalation"* (77%), "exposure to chemicals" (77%), *"rupture"* (53%), *"fall of blocks and sprayed concrete fragments"* (83%), *"collapse"* (83%), *"fall of person on the same level/to a lower level"* (73%), *"musculoskeletal problems"* (67%), *"run-overs"* (90%), *"exposure to biological substances"* (23%). For *"exposure to biological substances"*, 63% of the respondents said that CEM and TBM had the same Rm. The case of *"fire smoke inhalation"* is interesting: although most respondents said it was higher in CEM, the average Rm value given was higher in TBM.

Figure 1 represents the average Rm for each risk per method.

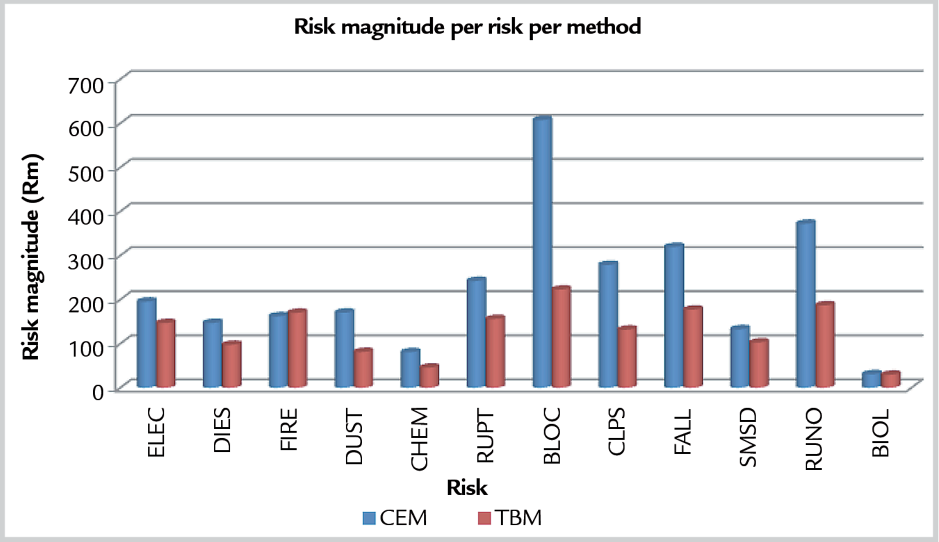

Figure 1
Rm per risk per method.

These results confirm (and now quantify) what some of the qualitative approaches have already said about CEM being less safe and less healthy than TBM. Two main explanations come immediately to mind: 1) the number of workers exposed to risk is higher in CEM; and 2) there is a need to have a recess cut out on the ground, which increases the risks linked to diesel vehicles (namely roll-over/tipping and run-overs), the manual and mechanical handling of loads, the fall of person to a lower level, and rupture. Next, other explanations for CEM having higher Rm values than TBM (except for "fire smoke inhalation") are analysed, risk by risk.

a)**"Electrization, electrocution" - Rm(CEM)=195; Rm(TBM)=147** - High volume of temporary electrical installations (Tender and Couto, 2016), set (usually manually) at variable locations following the progress of the works (whereas in TBM they are fixed), and subject to impacts from physical objects (e.g., from vehicles) or chemicals (e.g., acids); the high voltage supply line to the excavation front is fixed to the non-concreted sidewalls (whereas in TBM they are already cast) and repositioned during the final lining operations; and the final lining requires mobile structures (since they are completed in-situ) with dedicated electrical installations (e.g., to power tools for welding waterproofing sheets).

b) **"Diesel gas inhalation" - Rm(CEM)=147; Rm(TBM)=97** - Use of diesel equipment for loading and removing muck, whereas in TBM the muck is loaded through the cutting head (not diesel) and removed by electric or diesel engines; increased use of diesel lifting equipment for scaling and installation of stabilization devices; and greater quantity of materials to be transported, in diesel equipment, for the execution of sprayed concrete, waterproofing, reinforcement, formwork and concreting.

c) **“Fire smoke inhalation”** - **Rm(CEM)=162; Rm(TBM)=170** – Higher degree of mechanization in TBM with a greater number of electrical and hydraulic infrastructures for the various works that have to be carried out by the tunneling machine. CEM requires the use of more varied and less mechanized equipment.

d) **“Rock mass and sprayed concrete dust inhalation“** - **Rm(CEM)=170; Rm(TBM)=81** - There is no physical separation between the excavation face and other areas, allowing dust from the excavation to travel; the muck removal equipment lifts the dust from the ground, whereas in TBM the muck goes from the cutting head to locomotives/conveyors, thus minimizing the dispersion of pollutants (Labagnara, 2013), and the ground is already lined with prefabricated segments, which are more regular and less prone to mud creation; and in CEM, the operators/drivers often leave the relative insulation of the cabins (which does not happen in TBM), thus being exposed to dust.

e) **“Exposure to chemicals” – Rm(CEM)=80; Rm(TBM)=45** - Use of more chemicals in-situ for final lining; more welding and cutting operations (with harmful fumes); more relevant contact with concrete, either sprayed or for final lining; greater numbers of vehicles and equipment requiring servicing; and repairing concrete lining in-situ, whereas in TBM this is done outside the tunnel, as part of the prefabricated segments industrialized quality control.

f) **“Rupture”** - **Rm(CEM)=242; Rm(TBM)=156** - Increased exposure of support infrastructures to external agents (e.g., bumps or dust), due to the fact that the structures do not have a fixed location, and have to be disassembled and reassembled as the final lining progresses. In TBM, the support structures are better protected from damage, since they are part of the tunneling machine, and the final lining is installed immediately following excavation, with no need for repositioning; and in CEM there is increased use of lifting equipment (chains, slings, belts), in particular in definitive lining.

g) **“Fall of blocks and sprayed concrete fragments”** - **Rm(CEM)=607; Rm(TBM)=222** - Workers need to be in areas not protected against the fall of blocks before the final lining is applied; and the construction uses sprayed concrete, fragments of which may fall if it fails to reach enough resistance to self-sustain (Tender and Couto, 2017).

h) **“Collapse”** - **Rm(CEM)=278; Rm(TBM)=131** - Mobile equipment in CEM is more exposed to pavement collapse (Tender *et al.*, 2017b). In TBM, the equipment used is either part of the machine or runs on tracks, and the use of prefabricated segments avoids concrete mixers in the tunnel; and in CEM, there is great use of mobile structures for final lining, which are prone to disengagement or interconnections ruptures.

i) **“Fall of person on the same level/to a lower level”** - **Rm(CEM)=319; Rm(TBM)=177** – Greater contact of workers with wet and irregular ground, making it hard for them to move, namely when handling manual loads. The use of mobile stairs in the excavation face, for e.g. topographical marking, increases the risk of fall of person to a lower level (in TBM, this risk occurs inside the excavation chamber, namely in the replacement of cutting discs); more frequent use of lifting platforms and temporary mobile structures (Tender *et al.*, 2017b), generally with the guardrails installed on-site (instead of platforms belonging to the tunnel boring machine and fitted with factory-fitted guards or, in the case of prefabricated segments, outside the tunnel); and a higher number of mobile equipment with potentially slippery steps (if any) that workers have to climb.

j) **“Musculoskeletal problems”** - **Rm(CEM)=132; Rm(TBM)=103** - Heavier physical effort, handling heavier loads in varied shapes (Jodl and Resch, 2011); free access to the floor adjacent to the excavation face, with loose blocks at different heights that impede foot traffic; the entire excavation cycle, due to its low mechanization, requires more manual intervention of tools, materials (e.g. stabilizing devices or formwork parts), equipment and components, pointed, cutting, projectable (or falling from higher levels), or heavy-weight; and more time spent in postures in effort (due to the lower degree of mechanization) worsened by the manual handling of loads.

l) **“Run-overs”** - **Rm(CEM)=372; Rm(TBM)=187** - Greater amount of mobile equipment, less automated and a greater number of blind spots.

m) **“Exposure to biological substances”** - **Rm(CEM)=30; Rm(TBM)=29** - Greater direct contact with possibly contaminated excavated rock mass; and greater number of workers, in close contact with one another, which increases the likelihood of virus and bacteria spreading.

A2 – The work phases that have the highest levels of risk are, in hierarchical order, the 1st, 2nd and 3rd (both in CEM and TBM).

Figure 2 represents the Rm per work phase.

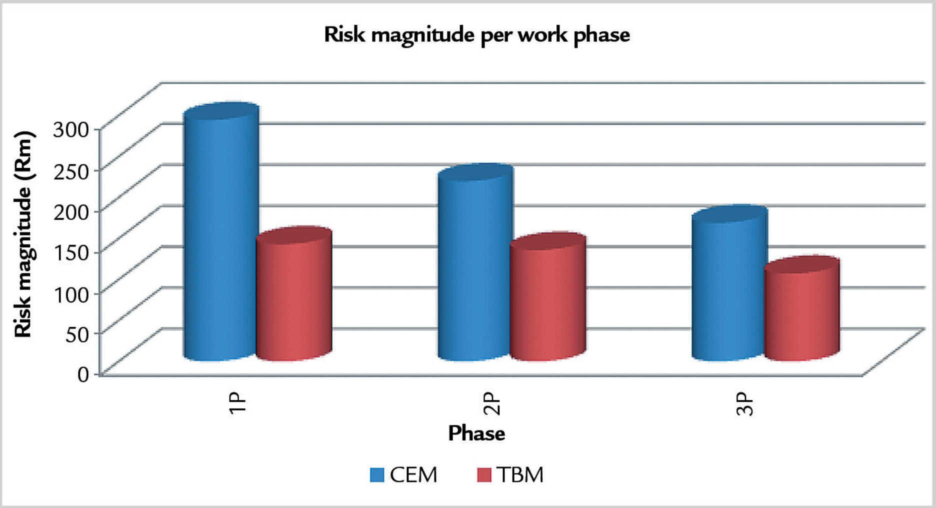

Figure 2
Rm per work phase.

In the three phases, CEM has higher levels of risk than TBM, and the Rm difference decreases from the 1st to the 3rd phase. The results obtained for CEM, which indicate the first phase as the most relevant, contradict Anerizis, who pointed out that the greatest risks would appear in the third phase, namely for workers associated with the installation of waterproofing systems, formwork/concreting or assembly of reinforcements(Aneziris *et al.*, 2010).

The importance of the first phase compared to the rest can be explained by the fact that most of the work that requires direct contact with the rock mass is carried out in this phase, and the presence of workers and equipment in the same space reaches its peak.

The following risks do not follow this general trend - Rm(F1)>Rm(F2)>Rm(F3).

a) CEM

a) **"Electrization, electrocution" - (Rm(F1)=220)>(Rm(F3)=202>(Rm (F2)=164)** – The fact that Rm(F3) is greater than Rm(F2) is justified by the greater use and mobilization of electrical installations in F3.

b) **"Fire smoke inhalation" - (Rm(F1)=188>(Rm(F3)=181)>(Rm(F2)=117)** - The fact that Rm(F3) is higher than Rm(F2) may be due to the greater quantity of combustible materials used in F3.

c) **"Exposure to chemicals" - (Rm(F3)=108)>(Rm(F2)=104)>(Rm (F1)=29)** - The fact that Rm(F3) is higher than the rest may be due to direct contact with several chemicals, such as products for waterproofing or associated with the final lining. The fact that Rm(F2) is higher than Rm(F1) may be due to the stabilization works, much associated with chemical treatments of the rock mass.

d) **"Fall of person on the same level/to a lower level" - (Rm(F3)=382)> (Rm(F1)=315)>(Rm(F2)=261)** - Contrary to the general hierarchy in relation to Rm(F3), because a large part of the final lining work, namely in the upper side wall and in the crown, must be carried out in height.

e) **"Musculoskeletal problems" - (Rm(F3)=162)>(Rm(F2)=131>(Rm (F1)=104)** - The fact that Rm(F3) is higher may be due to the high amount of work associated with the assembly of materials (waterproofing, reinforcements and formwork) for final linings. The Rm(F2) is justified by the greater number of workers employed for stabilization activities, especially in emergency situations.

b) TBM

a) **"Electrization, electrocution" - (Rm(F1)=191)>(Rm(F3)=131>(Rm (F2)=117)** - The fact that Rm(F3) is greater than Rm(F2) may be due to the greater moving of electrical installations in F3.

b) **"Rock mass and sprayed concrete dust inhalation" - (Rm(F2)=106> (Rm(F1)=102)>(Rm(F3)=35)** - The fact that Rm(F2) is greater than Rm(F1) may be due to the higher exposure to dust from the sprayed concrete in F2.

c) **"Exposure to chemicals" - (Rm (F2)=65>(Rm(F1)=36)>(Rm(F3)=35)** - The fact that Rm(F2) is higher than Rm(F1) may be due to the greater use of chemicals required in F2 for treating the rock mass.

d) **"Rupture" - (Rm(F2)=195>(Rm (F3)=150)>(Rm(F1)=122)** - The fact that Rm(F1) is lower than the rest is due to less load handling (and less use of lifting accessories) in F1.

e) **"Fall of blocks and sprayed concrete fragments" - (Rm(F2)=347 >(Rm(F1)=245)>(Rm(F3)=75)** - The fact that Rm(F2) is greater than Rm(F1) may be due to workers being closer to the excavation face, namely in emergency actions, in which works are carried out extremely near the critical zone.

f) **"Collapse" - (Rm(F1)=155> (Rm(F3)=131)>(Rm(F2)=109)** - The fact that Rm(F3) is higher than Rm(F2) may result from a greater use of temporary structures.

g) **"Fall of person on the same level/to a lower level" - (Rm(F3)=215>(Rm(F2)=192)>(Rm(F1)=124)** - The positioning of Rm(F3) may be due to the fact that the assembly of prefabricated segments is one of the few height jobs to be carried out in the TBM, except for its assembly and disassembly. The positioning of Rm(F2) may result from the stabilization solutions requiring a greater volume of work in height.

h) **"Musculoskeletal problems" - (Rm(F3)=131>(Rm(F2)=108)>(Rm (F1)=69** - The Rm(F3) can be justified by the very close movement between workers, vehicles and segments. As for Rm(F2) being higher than Rm(F1), it stems from the greater number of workers required for the application of stabilization solutions.

i) **"Run-overs" - (Rm(F1)=245>(Rm(F3)=167)>(Rm(F2)=148)**-The fact that Rm(F3) is higher than Rm(F2) can occur due to the large amount of vehicles transporting segments to the erector area.

The highest risks, for each of the work phases and for each method, are as follows:

a) CEM – 1st and 2nd phases – fall of blocks and sprayed concrete fragments, run-overs, collapse; 3rd phase – fall of person on the same level/ to a lower level, run-overs, collapse;

b) TBM – 1st phase – fall of blocks and sprayed concrete fragments, run-overs, fire smoke inhalation; 2nd phase – fall of blocks and sprayed concrete fragments, fall of person on the same level/to a lower level, rupture; and 3rd phase – fall of person on the same level/to a lower level, run-overs, rupture.

A3 - The risks, in each method, that show levels that are not tolerable are: *for CEM* – 1st Phase - "Electrisation, electrocution", "Diesel gas inhalation", "Fire smoke inhalation", "Rock mass and sprayed concrete dust inhalation", "Rupture", "Fall of blocks and sprayed concrete fragments", "Collapse", "Fall of person on the same level/to a lower level", "Run-overs". 2nd Phase - "Rupture", "Fall of blocks and sprayed concrete fragments", "Collapse", "Fall of person on the same level/to a lower level", "Run-overs". 3rd Phase - "Electrisation, electrocution", "Collapse", "Fall of person on the same level/to a lower level", "Run-overs". *For TBM* –1st PHASE - "Fire smoke inhalation", "Fall of blocks and sprayed concrete fragments", "Run-overs". 2nd Phase - BLOC. 3rd Phase - "Fall of person on the same level/to a lower level".

A4 - The excavation method that presents higher propensity levels for risk factors is CEM. In all risk factors, the opinion of the respondents was that CEM has higher Rp than TBM, with an absolute majority - "Noise"(53%), "Vibration"(77%), "Extreme temperatures" (36%), "Stress"(36%). In these two last risk factors, the percentages of opinions that valued CEM equivalent to TBM were, respectively, 43% and 50%.

Figure 3 represents the average Rp for each risk factor per method.

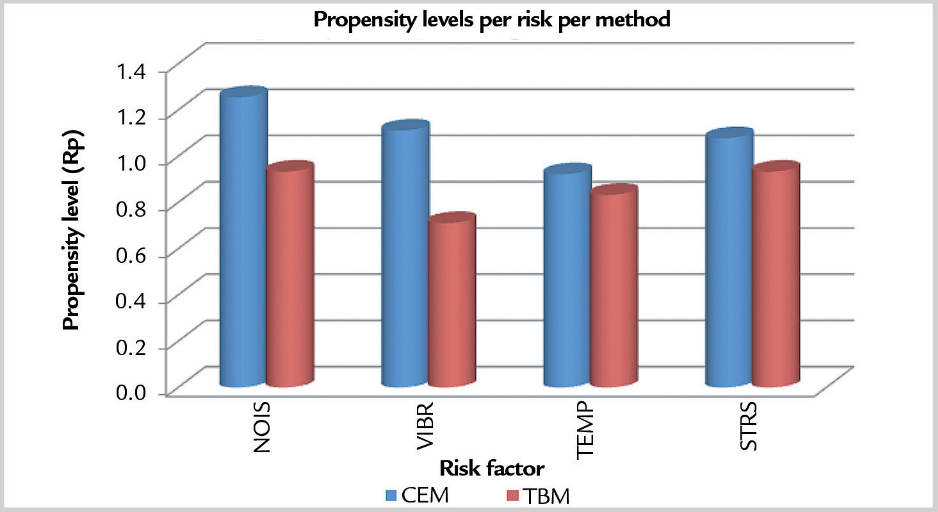

Figure 3
Rp per risk per method.

Two main justifications can be highlighted: the number of workers exposed to the risk in CEM is higher; and CEM requires a recess to be cut out on the ground, increasing the risks associated with the pruning of concrete from the shoe to fit the sidewall concrete and the manual vibration of concrete in the shoe, plus the increase in the amount of time the workers are exposed to heat and also stress, given that this structural element is crucial for the beginning of waterproofing. Other reasons justify this difference, and they are analysed below, risk by risk.

a) **"Noise" – Rp(CEM)=1.26; Rp(TBM)=0.93** - More noise level peaks (e.g. when the loader drops material into a dumper (Matos et al., 2016)), the greater number of times when the operators leave the cabins (e.g. to assemble\disassemble stabilization devices), and the various activities for final lining in-situ create high levels of noise (cutting shafts with grinding wheel, vibration of moulds).

b) **"Vibration" – Rp(CEM)=1.11; Rp(TBM)=0.71** - Higher level of vibration produced by mobile equipment; the ground where the equipment circulates is more irregular and more prone to vibrations; and greater use of pneumatic tools (e.g. for sample collection, etc.).

c) **"Extreme temperatures" – Rp(CEM)=0.92; Rp(TBM)=0.83** - The greater physical effort and greater number of workers (as it is less automated) force the worker to endure higher temperatures; higher temperature difference between inflated air and tunnel walls (uncoated in the CEM, at first); performing hot in-situ works for final lining (cutting of wood pieces, grinding, etc.); the maturation of the final lining concrete occurs inside the tunnel, so the high temperature is carried over to the surrounding air; and in the presence of radon, the exposure of workers to the excavation face is higher.

d) **"Stress" – Rp(CEM)=1.08; Rp(TBM)=0.93** - Greater volume of manual work, in a more aggressive occupational environment (aggravated by the shifts regime), requiring relevant efforts that induce fatigue to the workers; the non-ergonomic postures that the worker has to assume, due to the lower automation, are more inadequate; and greater psychological pressure to have progression in the works, which rely heavily on the presence and skill of the workers. At the same time, the posterior phases are more dependent on the previous ones, especially for the final lining.

A5 - The work phases that have the highest levels of risk propensity in each of the methods are, in order, the 1st, 2nd and 3rd (in both methods). This is justified because, in the first phase, workers are more subjected to the effects of these risk factors, by the nature of the work, by the equipment involved, and by the type of underground environment.

Figure 4 represents the Rp per work phase.

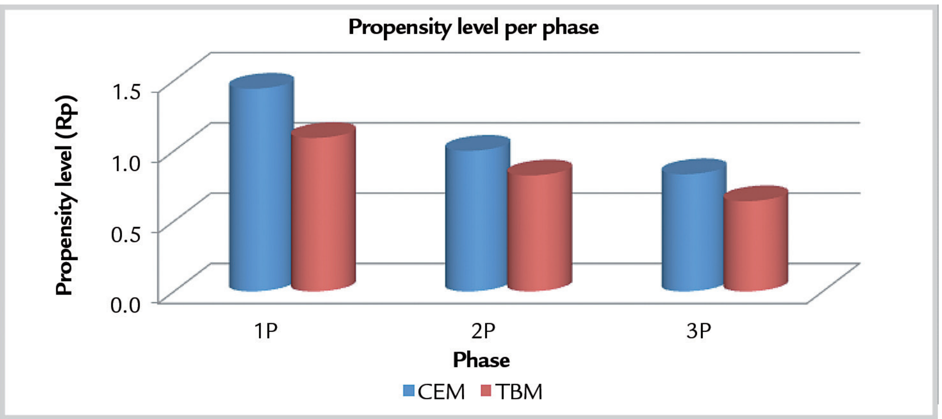

Figure 4
Rp per work phase.

All risks follow this general trend - Rp(F1)>Rp(F2)>Rp(F3).

The highest risk factors, for each of the work phases and for each method, are as follows:

a) CEM – 1st phase – Noise; 2nd phase – Noise, stress; 3rd phase – Stress, vibrations;

b) TBM – 1st phase – Noise, extreme temperatures; 2nd phase – Stress, noise; 3rd phase – Stress, extreme temperatures.

A6 - The risk factors that present non-tolerable levels in each method are: CEM - 1st Phase- "Noise", "Vibration"; "Stress" and TBM - 1st Phase- "Noise".

4. Conclusions

The results of a semi-quantitative risk assessment and a qualitative assessment of the propensity for the occurrence of risk factors were presented. The following conclusions can be drawn:

- The majority of the respondents have assessed the risks and risk factors (except for BIOL) in CEM as being much higher than those in TBM, with an absolute majority for most risks. The present study thus provides a scientific support, which was lacking, for some of the statements that stemmed from the individual, punctual and dispersed experience of some technicians.

- The WTF method used has characteristics of reliability, namely at the level of reproducibility, that allow for the result to hold true regardless of the respondent doing the assessment.

- CEM presents a level of risks and risk factors associated with its predominantly poorly mechanized characteristics, depending on large amounts of workers, exposed to the excavated mass and the occupational environment, while using a high volume of mobile equipment and temporary structures and materials (and their waste) to carry out the final lining.

- Many of the risks present in CEM are absent from TBM, due to its automated nature, with little human intervention in a less aggressive occupational environment, since the machine holds many of the necessary infrastructures in itself, and the prefabricated segments are made outside the tunnel.

In terms of future prospects, preventive measures should be explored to minimize risks and risk factors assessed as not tolerable. In addition, it is important to focus on the importance of those involved in the design and construction phases to minimize these risks, as well as assess the importance of information and training of workers. Conditions must also be made for a legislative framework in Portugal that will allow minimum requirements for tunneling to be established.

- The results obtained in the survey are in line with what the main author has been able to witness in real life working conditions, throughout his many years as a professional Safety and Health Coordinator in the work phase, namely in the Marão Tunnel. His many years' experience allows the author to say that these values accurately translate the technical reality and the risk levels and factors present in each of the stages of this kind of works.

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References

ANEZIRIS, O., PAPAZOGLOU, I., KALLIANIOTIS, D. Occupational risk of tunneling construction. ***Safety Science,*** v. 48, n. 8, p. 964-972, 2010.

AZEVEDO, R., ENSSLIN, L., JUNGLES, A. A Review of risk management in construction: opportunities for improvement. ***Modern Economy,*** v. 5, p. 367-383, 2014.

CABRAL, F., Veiga, R. ***Hygiene, safety, health and prevention of work accidents.*** Lisboa: Verlag Dashofer, 2009.

CARVALHO, F., MELO, R. Stability and reproducibility of semi-quantitative risk assessment methods within the occupational health and safety scope. ***Work,*** v. 51, p.591-600, 2013.

ESKESEN, S., TENGBORG, P., KAMPMANN, J., VEICHERTS, T. Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2. ***Tunnelling and Underground Space Technology,*** v. 19, p. 217-237, 2004.

FOULADGAR, M., YAZDANI-CHAMZINIA, A., ZAVADSKAS, E. Risk evaluation of tunneling projects. ***Archives of Civil and Mechanical Engineering,*** v. 12, p. 1-12, 2012.

FULCHER, B., HOME, L., HUDSON-SMITH, E. Decision process and criteria for selection of a preferred tunnelling method. In: RAPID TUNNELLING AND EXCAVATION CONFERENCE. New Orleans, Los Angeles: Society for Mining, Metallurgy & Exploration, 2015.

GADD, S., KEELEY, D., BALMFORTH, H. Pitfalls in risk assessment: examples from the UK. ***Safety Science,*** v. 42, p. 841-857, 2004.

HERMANUS, M. Occupational health and safety in mining—status, new developments, and concerns. ***The Journal of The Southern African Institute of Mining and Metallurgy,*** v. 107, p. 531-538, 2007.

INTERNATIONAL TUNNELLING ASSOCIATION 2016. ITA Report nº 17 - Recommendations on the development process for mined tunnels, Avignon, France, International Tunneling Association'.

JODL, H., RESCH, D. NATM and TBM – comparison with regard to construction operation. ***Geomechanics and Tunnelling,*** n. 4, p. 337-345, 2011.

KINNEY, G., WIRUTH, A. ***Practical risk analysis for safety management.*** CENTER, N. W. (ed.). California: Naval Weapons Center, 1976.

LABAGNARA. Tunneling operations, occupational S&H and environmental protection: A prevention through design approach. ***American Journal of Applied Sciences,*** v. 10, n. 11, p. 1371-1377, 2013.

LAMONT, D. Health and safety in tunnel construction. In: ITACET (Ed.). ***Health and safety in tunnel construction.*** Nova Delhi: ITACET, ITA-AITES, 2012.

MATOS, L., COELHO, A., BAPTISTA, J., COSTA, P. Relationship between production cycles and noise patterns in loading and transport operations in quarries. In: OCCUPATIONAL SAFETY AND HYGIENE, 4. London: Taylor & Francis,2016. p.473-478

RODRIGUES, M., AREZES, P., LEÃO, C. Defining risk acceptance criteria in occupational settings: a case study in the furniture industrial sector. ***Safety Science,*** v. 80, p. 288-295, 2015.

SINGH, P., ZOLDY, D. Drilling dilemmas. ***Tunnels and Tunneling,*** p. 46-51, 2014.

TENDER, M., COUTO, J. Analysis of health and safety risks in underground excavations – identification and evaluation by experts. ***International Journal of Control Theory and Applications,*** v. 9, n. 6, p. 2957-2964, 2016.

TENDER, M., COUTO, J. Study on prevention implementation in tunnels construction: Marão Tunnel's (Portugal) singularities. ***Revista de la Construcción,*** v.16, p. 262-273, 2017.

TENDER, M., COUTO, J., BRAGANÇA, L. The role of underground construction for the mobility, quality of life and economic and social sustainability of urban regions. ***Revista Escola de Minas,*** v.70, p. 265-271, 2017a.

TENDER, M., COUTO, J., BAPTISTA, J., GARCIA, A. Topics for the prevention of accidents in tunnels – the Marão Tunnel experience. In: OCCUPATIONAL SAFETY AND HYGIENE, 5. London: Taylor&Francis, 2017b. p.257-261.

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