Innovative techniques and technologies for underground construction and implications of OS&H

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A global overview of the technologies that can be applied for modern tunnelling construction taking into account the OS&H aspects is shortly presented in the paper.
Keywords: *Safety, OS&H, Underground Excavations, Innovation, TBM.*

Tecniche e tecnologie innovative per la realizzazione di opere in sotterraneo e risvolti di OS&H. *Un'analisi globale delle caratteristiche delle moderne tecnologie che possono essere applicate per consentire lo scavo di gallerie nell'ottica degli aspetti di OS&H è brevemente presentata in questo lavoro.*
Parole chiave: Sicurezza, OS&H, Scavo in sotterraneo , Innovazione, TBM.

Titolo francese. *Une analyse complète des caractéristiques des technologies modernes pouvant être appliquées pour permettre l'excavation de tunnels du point de vue des aspects OS&H est brièvement présentée dans ce travail.*
Mots clés: *Securité, OS&H, Excavation souterrain, Innovation, TBM.*

1 Introduction

In the past, underground excavations, such as tunnels and mines, have always represented a high-risk process regarding the safety of the workers as the confined spaces combined with the changing rock mass properties and its uncertainty, sometimes difficult to be correctly forecasted, can induce some critical OS&H aspect that have to be managed with both the excavation technique, the rock mass reinforcement and the supports installed in the tunnel or around it. Furthermore the massive use of full face machine and always better monitoring tools has allowed to obtain an important reduction of accidents and fatalities since the excavation process is better managed and the excavation voids stability are better guaranteed. As an example, during the excavation of the 15 km long Gotthard railway tunnel (1871-1881) the number of fatalities was around 200 persons, more than 10 per km of excavation while for the 13.6 km long Fréjus railway tunnel (1857-1871), excavated in the same years the number of fatalities directly linked to the excavation work was only 22 persons i.e. about 2 fatalities/km (Cialdini, 2011). This reduction of fatalities is mainly due to the better organization of the construction site works but is also due to the innovation and new techniques that were introduced and that helped to reduce the risk of a fatal accident. In modern tunnels it is possible to say that few fatalities can be registered during the construction of tunnels excavated both with conventional and with full face mechanized techniques.

Nowadays, the important improvements coming from the industry are ensuring that this reduction guarantees a working environment as safer as possible bringing also the safety standard to strict levels. First aspect that helped this process is the increase in the use of automation: while in the past the excavation work was done mostly by the workers themselves, the modern trend is automatize the risky processes. Probably the most important innovation in this technological process is the introduction of the Tunnel Boring Machines (TBMs), which basically reduces the direct use of the manpower on critical production and moreover are able to protect the working environment by possible failure of the tunnel by means of shields (for shielded machines) or protective grids (open TBM). In the next chapters, some aspects regarding the innovation that have improved the safety of workers in tunnelling process are described and will be discussed taking into account the two principal excavation technology, i.e. the conventional and the full face mechanized tunnelling.

Regarding OS&H risk control should be part of every stage of any tunnel project from conception to operations not only because it is a legal requirement in many jurisdictions but also because it is a basic duty of every professional engineer. Getting it right from the start is important since a retrofit may not be an option. In Europe the legal requirement to integrate OS&H risk control into planning, design and construction comes from the Temporary or Mobile Construction Sites Directive 92/57/EEC and designers should consider how they can ensure buildability, accessibility, operability, maintainability and recoverability of the tunnel they are designing without forgetting that all these aspects play a relevant role in health and safety risk control.

2. OS&H Risks in tunnel construction

The most important OS&H risks that are to be considered in tunnel construction, that affect both full face mechanized tunnelling and conventional one, have been clearly summarized by Lamond (2018) and they are:

Ground risks. That is probably the most important OS&H risk for everyone working underground and it includes groundwater and contamination risk. This risk can be minimised by undertaking a comprehensive ground investigation before the construction begins and probing ahead of the face during tunnelling. Machinery, plant and equipment risks. In Europe all plants and machinery used "at work" in Europe must comply with the Machinery Safety Directive 2006/42/EC. In addition, TBM manufacturers can follow a specific technical standard that is the EN 16191. EN 16191 covers the mechanical, electric, hydraulic safety of the machines, the controls systems and access of the machine, the fire precautions the noise and vibrations managements and the refuge chambers. With reference to plants and machinery for conventional tunnelling there are many relevant EN standards for machinery that includes: EN 12111 for roadheaders; EN 474 series for earthmoving machinery and EN 16228 series for drilling equipment.

Construction product safety and hazardous substances. The regulation EU 305/2011 requires that all the construction products meet the following criteria: mechanical resistance and stability; safety in case of fire; hygiene, health and the environment; safety and accessibility in use; protection against noise; energy economy and heat retention and sustainable use of natural resource. It is important to highlight that these concepts do not apply to all products that are at present used in tunnelling construction. There is a range of EU Directives requiring the control of exposures to carcinogens and other hazardous substances ad work. These EU directives set limits for exposure whilst at work to certain hazardous substances furthermore exposure limits are set for nitrogen monoxide and dioxide (that occur in diesel exhaust emission). These limits are proving to be very challenging and they require: very extensive ventilation or the use of battery/electric power instead of diesel power.

Since the general "Principles of prevention" require: to eliminate hazard / avoid risk, to combat risk at source , to adapt work to individual; to adapt to technical progress; to substitute products by less/non dangerous products; to set up collective protection over individual protection and to set up important instruction and training activities for workers, it is important to highlight how in the last years a great improvement has been developed in tunnelling design and construction to act in this direction.

3. Conventional tunnelling

This methodology, even though is the oldest and was used since the very past, has shown, in modern times, some important evolution that has positively influenced not only the tunnel production (i.e meters of excavated tunnel per day) but also the stability of the tunnel (reducing the ground risks) and the OS&H of the workers.

The reduction of ground risks has been achieved with an important improvement of the investigation techniques that can be used at the design stage but also the investigation ahead of the face has greatly improved both with faster drill rig but also with the systematic use of seismic investigations.

The improvement of the quality of ground reinforcing techniques, both related to the materials and installation technology has been really impressing: the grouting products both chemical and cement today allow to get better results than in the past as well as the face reinforcement ahead the face allow to stabilize the tunnel to be excavated to an extent that was not possible to be imagined only few years ago. On the other hand, these products are always more environmental friendly and they clearly follow the regulations regarding the construction product safety.

In the same time better and safer supports have been developed and used. And the automatization of the installation process has allowed to improve the safety of the process inside the tunnels including the support installation, drilling and mucking. As an example, the use of new types of steel arches with much better positioning device have been developed and some experiments have been carried out to join these machinery to the IT increased reality device to facilitate the process.

A great attention has been devoted to the use of surface construction machinery underground that is the practice sometimes still applies in some nations of the world. Such machinery is not designed for the underground environment and the lack of essential safety features and the machine robustness make these machines not available for the use in the underground environment. General construction machinery used underground should comply with the ISO 19296 "additional requirements for earthmoving machinery used underground". Great attention is today paid to: fire, impact with the tunnel walls, atmospheric contamination, restricted visibility and lighting, exhausted emissions, lifting of the pants and ever hoist protection.

With reference to shotcrete phase, as an example, which can be a danger for the workers' health both for the possible inhalation of concrete dust and a risk for the jobsite is the detachment of unstable concrete sprayed slabs occur before a complete hardening has occurred it can be observed that an important improvement of the installation phase with the use of modern robots able to keep the workers in a safe area during the excavation.

Usually the manual shotcreting is performed with the dry-mix technology, which is easy to handle but causes the cited problems. In the original applications, the worker was spraying the concrete as much as possible close to the area of interest: this is due to the fact that the shotcrete is effective while the nozzle is not more that 1m from the application area. The modern trend is to use a completely mechanized system by means of a robot that is substituting the physical presence of the manpower. The shotcrete operator is then located at a safety distance from the application area, in this way the risk is reducing substantially. Moreover, this kind of system is mostly working with the wet-mix principle, which is causing much less dust than in the dry-mix one. The quality of the installed shotcrete and its short and long term stability is a topic of great interest.

Regarding the drilling phase, the technology evolved in a similar way than in the shotcreting: while previously the holes were performed manually, nowadays the work is carried out through drilling jumbos. This innovation, in addition to create a safer environment for the operators, who are now protected by the cabin and are not anymore in proximity to possible unstable wedges that might slide or fall from the front, allowed companies to improve the mechanization and automation of the process. The machines are now maneuvered by computers which are fully programmed according to the original design, in this way uncertainties and deviations are reduced and the construction site can proceed with lower risk. Furthermore, some producers have developed devices with battery power for travel thus reducing the emissions and the machine are compliant the EN 16228. Another important phase which might cause accidents, and that usually is well planned and defined in the organization of the construction site, is the mucking. In this case, on the contrary of the previously described operations, the operator is always protected in the cabin, so the risk is lower, but the other workers in the site might be potentially run over by the loaders or trucks, especially in complex sites. As a matter of fact, mucking is usually representing a time demanding operation considering a single round of excavation, so it is difficult to organize the site in a way that no worker is present along the path of hauling. A recent innovation is represented by the automated Left-Hand Drive – LHD, especially for the mine use: in this way the system allows to perform a fully automated mucking. In automatic mode, the machine follows the reference trajectory by correcting its heading when required. To do this the navigation system constantly measures the position and heading of the vehicle using dead reckoning. Due to the drift of dead reckoning the position and heading estimates must be corrected frequently enough. The environment model is used to estimate the drift which is then corrected.

In this scenario, the future of the site is of course to remove completely the operators from the direct contact with the potentially risky areas. A better use of the devices to control the position of the workers underground is now usually installed in the large job sites such as the long and deep alpine tunnels

While this represents the ideal scheme to operate, adding automations in complex environment as an underground construction site is a difficult issue. Higher is the automation and lower is the flexibility of the system, and in conventional construction sites there are several overlapping operations working in parallel and which might change the scheduling independently. This is also a reason why the market is going more and more towards the use of mechanized systems such as TBMs, which are exactly designed to collect all the operations into a single machine. Of course this is valid in certain conditions, smaller sites and complex compounds as mines cannot be effective if using this technology, so it is necessary to continue the development also of conventional methods.

4. Full face mechanized tunnelling

In general, this method represents the most widely used system for modern excavation of tunnels. Obviously in this field companies are investing more and more resources to improve the technologies to be used with regards the EN 16191 – TBM safety the following issues are relevant: mechanical, electrical and hydraulic safety, control systems, fire precautions, noise and vibration, refuge chamber. In this way both the productivity and security conditions can be improved. This necessity has brought the producers of TBM machines to invest a lot of resources to obtain excavation machines more and more adapted to the needs of modern times.

Surely among the TBM machines the most innovative types are represented by the ones able to apply a counterpressure directly to the excavation front. Especially EPB, able to apply the pressure through the muck conditioned with foams or other materials, and Slurry shields/Hydroshields, which apply the counterpressure with the bentonite, are playing a crucial role in the innovation.

The use of EPB technology being the most frequently used has become more and more widely applied also thank to the improvement of the quality and feasibility of the conditioning agents that are always more environmental friendly and more effective in achieving a good conditioning.

In fact, these technologies allow to create a safe environment for a process that might be thought risky, because the workers and the equipment are always protected under the shield in the area close to the front and under the final segmental lining in the rest of the tunnel. Moreover, the counterpressure ensures the stability of the front and does not allow unexpected flows of water thought the excavation front, which might be fatal on the safety point of view.

Interesting recent cases of these kind of machines are represented by the EPB which was involved in the excavation in 2013 of the Sparvo tunnel and the one directly involved in the excavation of Santa Lucia tunnel, both part of the "Variante di Valico" between Bologna and Firenze A1 highway. These machine, beyond being among the largest EPB machine in the world, are able to excavate in a gaseous environment thanks to a protective system. This system allows to keep natural gas (CH_4), naturally present into the rock mass, into a closed circuit which seals the excavated muck from the tunnel environment, in this way the workers are not directly in contact with the gas. Usually in a regular EPB machine the muck, once excavated and extracted from the plenum chamber through a screw conveyor, is falling into a belt conveyor which transports the material outside the tunnel. In this special machine, on the contrary, the belt conveyor has a fire dump protection, as it is collected into a double-shelled pipe, with the double-wall pressurized at 40 mbar to avoid gas leakage from the pipe itself. Additionally, the main conveyor is equipped with CH_4 sensors monitoring constantly the presence of gas and it has a so called flushing mode to increase the ventilation into the pipe. Moreover, all the equipment present into the pipe is Ex-proof, at least IM2 class.

The gas monitoring and protection in this machine is not limited just to the mucking part, but to prevent large penetration of gas during the excavation, the plenum chamber has been kept always full, thus in complete closed mode. In order to verify the absence of voids (with potential presence of natural gas),. Another device useful for this detection is a viscosity detector which constantly monitor and verify the presence of a certain value of viscosity into the chamber, meaning that there is always a good quality muck.

For all this protective system, a complex and widespread network of sensors is installed in the area near the excavation front, where the gas is potentially located. In the Sparvo machine the ventilation and gas monitoring is accessible from the control cabin through a remote controlled system. In total 13 gas sensors are distributed over shield, backup and excavation chamber. The remaining hazardous installation would remain the ventilation system, that in the regular EPB machines would mix the fresh air with the potentially poisonous one. To deal with this problem, a redundant ventilation system (equipped with 2 independent lines) with by-pass to the belt channel to flush up to 23 m^3/s of air is installed. In this way the muck, while into the double-shelled pipe, is travelling into a depressurized environment.

An important aspect to be taken into account while choosing the TBM type depending on the tunnel project, is represented by the environmental/geological conditions, but also on the logistics. While for example EPB is suitable for finer soils and does not require large service infrastructures outside of the tunnel, for coarser soils this machine is not effective, and the Slurry is preferred. But quite often the geology is very heterogeneous, thus if the machine is working effectively in one part it might stuck in another portion of the tunnel, causing potential dangers also on the safety point of view. This is due to the fact that the procedure to make the machine again working, extra measures have to be used, and quite often these are not foreseen. So these measures might bring non-foreseen risks which have to be phased and well organized by the construction site. In order to avoid these situations, TBM manufacturers are trying to work on a "perfect" machine, able to work as standard operation in basically all the geological environments, and they introduced the so-called "multi-mode TBMs".

An example of these machines is represented by the recent "Variable Density" concept introduced by Herrenknecht (first absolute breakthrough with this type of machine in Kuala Lumpur in 2014) which can work in open (half-empty excavation chamber and no counterpressure at the front), earth pressure balance – EPB, high density slurry (counterpressure with bentonite slurry, mucking through the screw conveyor) and standard slurry mode (counterpressure with bentonite slurry, hydraulic mucking with slurry). This important innovation, despite its direct higher cost (the machine itself is almost double price than a regular EPB), allows to create a much safer construction site, which on a large scale can bring to a lower cost due to higher utilization factor. This goal is reached by switching between modes of operation without stopping the machine, using the so-called seamless transition principle. The transformation between EPB face support and slurry face support in the tunnel is performed without the need of modification or chamber intervention. The combined system works as full size and quality face support systems for both EPB and slurry operation, and ensures safe and fully controlled conditions for face support during mode change.

4. Conclusions

OS&H is a key issue for a successful tunnel construction. Today designers should not develop a tunnel design without starting from these aspects or considering them, just a duty of the construction company. The design choices directly influence the OS&H not only with reference to the tunnel stability but also with the underground environment where the workers have to operate following the "protection through design" approach.

The systematic and increasing use of full face machines has allowed to reduce these risks to a great extent but a lot of works has still to be done since these machines are more and more complex and require a great carefulness in the quality of their management.

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