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Life safety applied in full face excavation

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ABSTRACT: The management of the risks associated with tunnelling work follow a systematic process, which involves identifying hazards, assessing and controlling risks. Tunnel design is different to surface structure design, because it is difficult to accurately predetermine geological and stress conditions, properties and variability along the tunnel. ADECO-RS (Analysis of Controlled Deformation in Rock and Soil) defines a method for design and construction of tunnels. The paper summarizes the main issue of this method, which is related to the design procedure and approach that ensure maximum safety level, accurate scaling and job site organization. During the construction stage (operational phase) the work process is to be verified by monitoring the Real Deformation Response. Control is developed by perfecting the design, balanced on the basis of the results of the Analysis and on the field of the possible variables that have already been planned in the design stage. The management of the different work phases is a fundamental safety aspect during tunnel construction. Limiting the number of the operators at the face and their occupancy time in that area significantly increases safety level of the excavation process.

1 INTRODUCTION

The construction of underground tunnels, shafts, chambers, and passageways are essential yet dangerous activities. Working under reduced light conditions, difficult or limited access and egress, with the potential for exposure to air contaminants and the hazards of fire and explosion, underground construction workers face many dangers.

Many aspects of tunnel design influencing whether a tunnel is constructed safely, like tunnelling in rock or soft ground, are decided in the concept design stage. During this phase duty holders should consult and plan to manage risks which may occur when constructing, using and maintaining the tunnel. Consultation between duty holders will give a better understanding of the time needed for geotechnical investigations, tender preparation, construction and potential delays. The principal contractor must ensure a work health and safety management plan is prepared for the tunnelling work before tunnelling work starts. The client should include this requirement in contract documents. Underground construction is an inherently dangerous undertaking, and hazardous conditions are given mainly by - but not limited to - falls from height, falling objects, hit by machinery, handling of heavy objects.

2 THE DESIGN AND CONSTRUCTION OF TUNNELS

Estimates of uncertainties and risks of the construction process are essential information for decision-making in infrastructure projects. The construction process is affected by different types of uncertainties. We can distinguish between the common variability of the construction process and the uncertainty on occurrence of extraordinary events, also denoted as failures of the construction process or of the geological model. In tunnel construction, a significant part of the uncertainty results from the unknown geotechnical conditions. The construction performance is further influenced by human and organizational factors, whose effect is not known in advance. All these uncertainties should be taken into account when modelling the uncertainty and risk of the tunnel construction.

Underground structures are man made objects constructed in heterogeneous and complex natural environment. For planning and designing of the structures it is thus crucial to describe the behaviour of the geological environment by parameters, which can be used in the structural analysis and for planning and monitoring of the construction process.

For reliable predictions, it is essential to realistically estimate the parameters of the probabilistic model. This is so true especially for the definition of geological and geotechnical model which often is characterized by uncertainty due to:

- low number and poor quality of investigations
- wrong sampling
- wrong technological choice for in situ and laboratory tests
- unfair geotechnical characterization

It is fundamental try to solve this possible initial lack of information because geological and geotechnical knowledge represent the basis of tunnel design.

In any case there are practical limits to the detail in which an investigation can describe the ground to be encountered by a tunnel. The most widely accepted and successful way to deal with the uncertainties inherent in dealing with geological materials came to be known as the observational method (used since 1969).

The European Standard EN 1997-1: Eurocode 7. Geotechnical design - Part 1: General rules in paragraph "2.7 Observational method" includes the following definition:

(1) When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the
(2) approach known as "the observational method", in which the design is reviewed during construction.
(3) P During construction, the monitoring shall be carried out as planned.
(4) P The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put into operation if the limits of behaviour are exceeded.
(5) P Monitoring equipment shall either be replaced or extended if it fails to supply reliable data

of appropriate type or in sufficient quantity.

The application of observational method should lead to a fine tuning of the design during the construction works.

2.1 *The design and construction stages*

According to the A.DE.CO-RS Approach for full face tunnel excavation to frame the design and the construction of underground works it is necessary to divide them into two chronologically separate moments (Figure 1): a design stage and a construction stage (Lunardi, 2008). The design stage consisting of:

- survey phase: referred to the geological, geomechanical and hydrogeological knowledge of the ground and to the analysis of the existing natural equilibriums;
- diagnosis phase: referred to the analysis and the theoretical forecasting of the behavior of the ground in terms of Deformation Response, in the absence of stabilizing operations, according to the stability conditions of the core-face;
- therapy phase: referred, firstly, to the definition of the methods of excavating and stabilizing the ground to control the Deformation Response; and subsequently, to the numerical evaluation of the effectiveness of the solutions chosen; in this phase the section types are composed and the possible variability depending on the actual deformation behaviour of the tunnel in the excavation phase, which will be measured during the operating phase

Stage	Phase	Description
Design	Survey	Analysis of existing natural equilibriums
	Diagnosis	Analysis and prediction of deformation phenomena (*) in the absence of stabilisation measures
	Therapy	Control of deformation phenomena (*) in term of stabilisation systems chosen
Construction	Operational	Application of the stabilisation instruments for controlling deformation phenomena(*)
	Monitoring	Control and measurement of deformation phenomena(*) as the response of the rock mass during tunnel advance (measurement of extrusion at the core-face and of convergence at the contour of the cavity and at varying distance from it, inside the mass of the ground)
	Final design adjustments	Interpretation of deformation phenomena (*) Balancing of stabilisation systems between the core-face and the perimeter of the cavity

(*) Deformation phenomena in terms of extrusion at the core-face and of convergence at varying distance from it, inside the mass of the ground

Figure 1. Design and Construction Stage.

The construction stage consisting of:

- operational phase: referring to the actual construction of the tunnel, in which the application of the stabilizing instruments for controlling the Deformation Response is implemented.
- monitoring and final design adjustment phase: during the course of the work, referring to the measurement and experimental interpretation of the actual behaviour of the ground to excavation in terms of Deformation Response, for the finalization and the balancing of the stabilizing systems implemented between the core-face and the excavation perimeter, and for checking the chosen solutions by means of comparing actually measured deformations with the ones that are expected theoretically.

The behaviour of the face is then influenced by these factors:

- Geotechnical parameters of the soil (strength and deformability)
- Overburden of the tunnel (geostatic stresses)
- Size of the tunnel (diameter and shape)
- Excavation system
- Constructional procedures

The construction of tunnels consists in two main phases: tunnel excavation (including construction of the tunnel support) and equipment of the tunnel with final installations (ventilation system, lighting and safety systems etc.). The latter is not discussed in this paper. Three main tunneling technologies are commonly utilized in present practice (mechanized, conventional and cut&cover) but the paper paid a special attention to the conventional tunneling excavation method.

3 TUNNEL OPERATIONAL CYCLE

According to definition of International Tunnelling Association (ITA-AITES, 2009), the conventional tunneling technology is construction of underground openings of any shape with a cyclic construction process of:

- excavation, by using the drill and blast methods or mechanical excavators (road headers, excavators with shovels, rippers, hydraulic breakers etc.)
- mucking
- placement of the primary support elements such as: steel ribs or lattice girders, soil or rock bolts, shotcrete, not reinforced or reinforced with wire mesh or fibres.

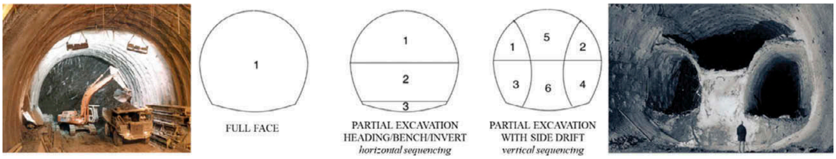

Figure 2. Typical excavation sequencing types in conventional tunneling.

One cycle of the construction process is denoted as round and the length of the tunnel segment constructed within one round is denoted as round length.

The excavation method, round length, excavation sequencing and support measures are selected depending on the geotechnical conditions and cross-section area of the tunnel. The excavation method, round length, excavation sequencing (Figure 2) and support measures (in sum denoted as the construction method in this paper) are selected depending on the geotechnical conditions and cross-section area of the tunnel. The decisive factor for the selection is the stand-up time of the unsupported opening. To give an example, a tunnel constructed in very good ground conditions with long stability of unsupported opening can be excavated full face with round length of several meters and it requires only simple support. On the contrary, in difficult ground conditions, shorter round length and demanding support measures must be applied. In poor ground conditions, auxiliary construction measures can be used. These are for example jet grouting, ground freezing, pipe umbrellas or face bolts.

The conventional tunneling technology has many modifications depending on the local experience and geological specifics.

3.1 *The conventional tunnel excavation common risk*

The risk is inherent all engineering applications. The common practice area of mining and civil engineers, tunnel construction, is also prone to several hazards originating from different sources.

In the early design and tender and contract negotiation phases, certain risks may be transferred, either contractually or through insurance, others may be retained and some risks can be eliminated and/or mitigated. In the construction phase, possibilities of risk transfer are minimal and the most advantageous strategy for both owner and contractor is to reduce the severity of as many risks as possible through the planning and implementation of risk eliminating and/or risk mitigating initiatives (Eskesen S.D., 2004).

Underground workers are at risk for serious and often fatal injuries. Some hazards are the same as those of construction on the surface, but they are amplified by working in a confined environment. Other hazards are unique to underground work. These include being struck by specialized machinery or being electrocuted, being buried by roof falls or cave-ins and being asphyxiated or injured by fires or explosions. Tunnelling operations may encounter unexpected impoundments of water, resulting in floods and drowning.

Control measures should be identified to eliminate or minimise, so far as is reasonably practicable, risks associated with tunneling work. These mostly arise from working underground and can be identified during consultation and the risk assessment process.

The risks related to the conventional tunneling excavation methods can be listed as follow:

– Rock Fall from crown and face
– Small working spaces (Figure 3.a)
– Numbers of Workers on face
– Small size equipment (Figure 3.b)
– High water and mud inflow
– Gas inrush
– Falls from height
– Loss of lighting
– Manual tasks like handling air tools, drill rods, supports, cutters
– Heat stress

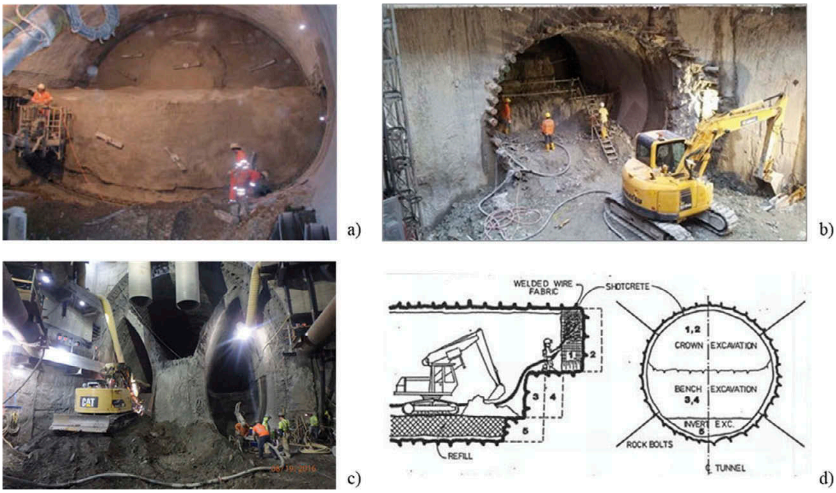

Figure 3. Risks related to the conventional tunneling excavation methods: a) Small working spaces; b) Small size equipment; c) e d) synchronized actions.

but the most critical issue is the synchronized actions highlighted by the Figure 3c and Figure 3d (ITA-AITES, 2009). Each work phase is characterized by specific risk and the overlap of different actions cause an exponential increase of the risks.

4 SAFETY & HAZARD MITIGATION

Underground construction is inherently a dangerous undertaking. Work progresses in a noisy environment in close quarters with moving heavy machinery. Careful attention must be paid to the layout of the worksite and workers must be protected at all times.

In order to excavate the opening required for the tunnel, the natural properties of the ground are disturbed. The ground is rarely a homogeneous mass but has been subjected to massive natural forces and has been substantially altered. Once the opening has been excavated it must be supported in order for the workers to be protected from falling material, collapse or other deterioration of the tunnel roof or crown. The excavation can be carried out in different methods depending on the type of material to be excavated.

4.1 *The hazards control in underground construction*

The best practice establishes a process and determines controls for achieving reduction in risks using the following hierarchy:

- Hazard elimination: Avoiding risks and adapting work to workers, (integrating health safety and ergonomics when planning new construction site)
- Substitution: Replacing the dangerous with the less or non-dangerous (increasing technology)
- Engineering controls: implementing collective protective measures
- Administrative controls: Giving appropriate instructions to workers
- Personal protective equipment (PPE): Providing PPE and instructions for PPE use/maintenance

Every step of the underground excavation should be planned with safety in mind. The normal surface safety concerns are also appropriate and often amplified for underground construction including: workers must be safeguarded from falling from the work platforms used in the mining process, from being struck by the moving equipment and from electrocution amongst many hazards. However there are also many additional hazards that workers must be protected from and guarded against.

It is typically the job of the Construction Engineer to plan on making the tunnel opening stable to allow workers to move freely and without the concern of falling material.

The contractor should ensure that suitable and sufficient tunneling equipment for the type of work to be carried out is provided and is operated and maintained in accordance with manufacturers' instructions. Furthermore, the contractor should reduce the risk to workers underground through the elimination or control of hazardous materials and processes.

The full-face excavation requires a specifically risk analysis for the construction process applied. The risks are well known and should be managed in a properly way.

4.2 *Standard & Code*

Safety Issue has been considered an important topic since a long time. The first guideline dated back to 1941 with the Bulletin n. 439 of the Bureau of Mine (Washington, U.S.A.) titled: Some essential safety factors in tunneling.

Since late '90 and early '00 consistent and solid H&S regulations were adopted worldwide, such as: BS 6164: 2011. Code of Practice for Health and Safety in Tunnelling in the Construction Industry (UK) or NIR (IT) (the guidelines are several and each volume, identified by a number, is related to a specific topic, i.e. n. 41 operation close to the face).

The NIRs (Norme Interregionali), are the Interregional Rules of the Regions Emilia Romagna and Tuscany in Italy, developed by the Occupational Health and Safety department of the two regions, aim to achieve the highest safety levels in full face tunnel work. Each of them is a monothematic technical treatise containing design, construction, organizational, technological and operational solutions.

The regulations have been developed on the basis of problems and events recorded during the construction of High Speed Railway Line (section Bologna to Florence, total underground excavation 104,3 km) and Variante di Valico (total underground excavation length 62,2 km), which is the upgrading section of the A1 Milan-Naples motorway between Sasso Marconi (Bologna) and Barberino di Mugello (Florence).

Since 1998 until now 45 documents have been drawn up. NIRs have been exported to other regions by clients and contractors and have been adopted by various regions in Italy. Various professional figures, designers, service companies, manufacturers of equipment, machines and communication and control systems have contributed ideas to the development of solutions which were subsequently formalised in the Interregional Notes.

The scope of the NIRs is to increase safety at the construction sites of the Large Underground Works and they cover all the issues related to a project development from the design stage to the construction stage focusing the attention on Safety issue.

4.3 *The Italian experience*

The NIRs have been defined on the basis of Italian experience, as mentioned previously in this paragraph. The standards consider only full-face excavation method; this design choice is supported by previous experience in which this solution proved to be successful compared to the "partial excavation".

The approach is based mainly on two concepts (summarised by Figure 4:

- the significance of the deformation response of the ground during excavation, which the tunnel engineer has to be able to fully analyse and then control;
- the use of the advance-core of the tunnel as a stabilization tool to control deformation response and to get a prompt stability of the excavation.

Control of deformation response can be achieved:

Ahead of the face - regulating the rigidity of the advance core by means of pre-confinement of the cavity using different techniques depending on the type of ground, the in-situ stress and the presence of water. There are two different kind of interventions:

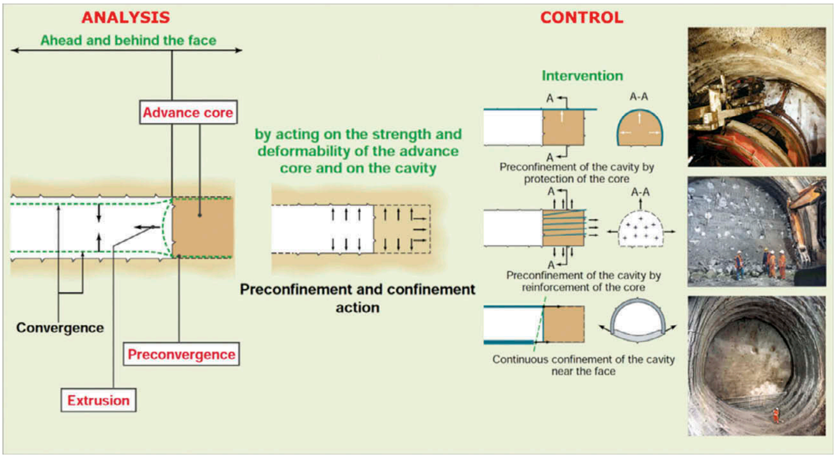

Figure 4. The main concepts of A.DE.CO-RS Approach.

– protective conservation is the one set in advance, working around the perimeter of the cavity to form a protective shell around the core able to reduce deformation on the core-face system (Figure 5.a);
– reinforcement conservation is the one set directly into the core of advance, to improve its natural strength and deformation parameters (Figure 5.b).

Down from the face - regulating how the advance core extrudes by means of confinement of the cavity closing the ring and making the preliminary lining rigid close to the face (Figure 6).

The A.DE.CO-RS approach and the NIRs application fitting perfectly to hierarchical method applicable for risks reduction during tunnelling construction (Figure 7). The excavation phase is the most dangerous work phase and the main benefit of ADECO adopted by the NIRs is the high industrialization level. Each operation is well defined and executed by small

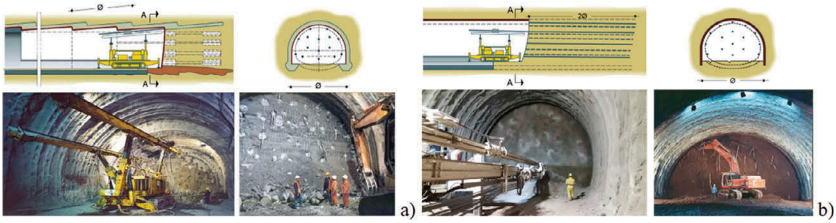

Figure 5. Example of conservation technique: a) Sub-horizontal jet-grouting around the cavity & in the core; b) Reinforcement of the core using glass-fibre elements.

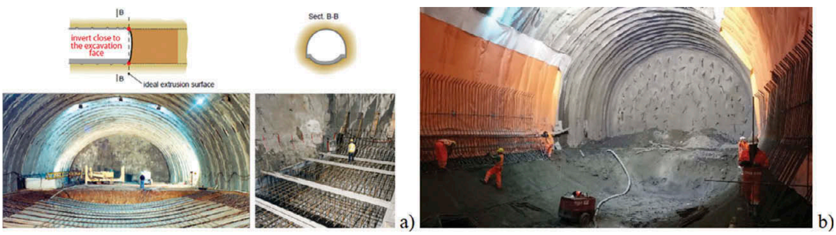

Figure 6. Example of conservation technique: a) Invert; b) advance core GFRP reinforcement and invert.

Figure 7. Relation between the risks reduction hierarchical method, A.DE.CO-RS approach and NIR.

number of experienced workers, using large equipment characterized by technological value which reduce the risk of human fault to a low level. The safety of workers during the excavation phase requires a unified approach and rational organization of the site in order to minimize the risks associated with the works and those related to the interference, the operating space and the execution times.

5 FULL FACE EXCAVATION & SAFETY ISSUES

With reference to the "full excavation face" method, the excavation proceeds through the use of an excavator equipped with a "hammer" or by drill and blast. Subsequently, after removing portions of unstable rock (scaling) a preliminary layer of concrete is sprayed on the excavated face and cavity portion. After this operation it is possible to install the primary lining constituted by steel arch and reinforced shotcrete.

Main advantages of the full-face excavation are related to the industrialization of the work phases: one of the great innovations is the simplification and cleanliness of the construction operations into the tunnel. There are always few workers moving into the tunnel (not more than six persons in each stage of construction), with few and powerful machines and equipment to be used), with a clear sequence of operations. There is never a superposition of different kind of interventions or operations. There is a direct relationship between the number of workers and of the machinery and safety: the less they are, the greater is the safety.

The relevant aspect with respect to the safety is for sure the layer dimensions of the working area. The full-face excavation method has a lot of benefits in term of safety but the concrete pre-lining spraied on the face and on the excavated portion of the cavity has a fundamental function preventing rock fall and local instability of the face and of the cavity. The huge dimension of the face (varying from 130 sm to 230sm) requires this procedure despite to the fact the area close to the face is forbidden to man works and operations. The NIR 37 titled "Guidelines for the safety of the excavation phase in tunnels bored with Conventional method" cover specifically this topic, underling the importance of this specific work phase.

5.1 *Work Phases*

With reference to the ADECO-RS Approach, a typical cycle-work for tunnel construction is reported in the following figures. The main phases are:

Ground reinforcement (Figure 8)

– Pre-confinement of the core-face, by means of fiber-glass reinforcements or grouting activities, or pre-support system, or drainages pipes ahead of the face (if necessary, according to face categories)

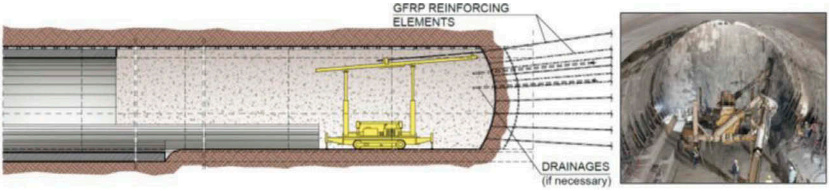

Figure 8. Ground reinforcement work phase.

Excavation & first lining installation (Figure 9)

- Full-face excavation (top-down), with excavation step depending on the geomechanical conditions, ranging from 1.0 m up to 3.0 m. The excavation will be made by drill&blast or by mechanical system, with concave shape.
- Placing of fibre-reinforced shotcrete on the face and on the cavity (for each excavation step as a preliminary lining for safety provision of the excavated section).
- Confinement of the cavity, placing steel bolts or steel ribs.
- Completing the first lining, placing fiber-reinforced shotcrete (or reinforced with wire-mesh).

Invert casting & final lining (Figure 10)

- Excavation and casting of side walls and invert (at a defined distance from the face).
- Waterproofing installation.
- Placing vault reinforcement (if required) and casting the final lining (at a defined distance from the face).

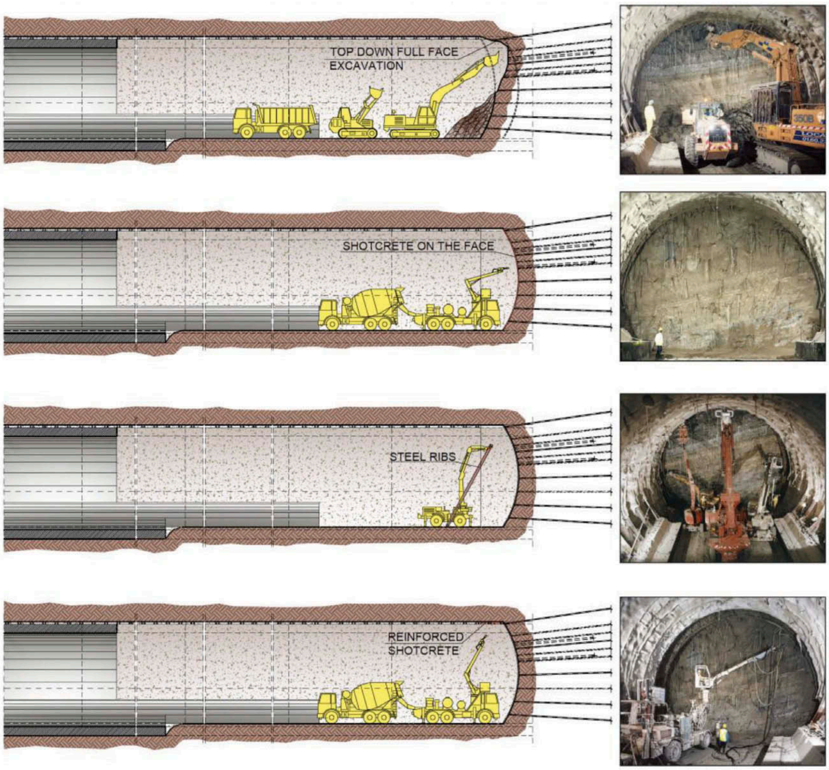

Figure 9. Excavation & first lining installation.

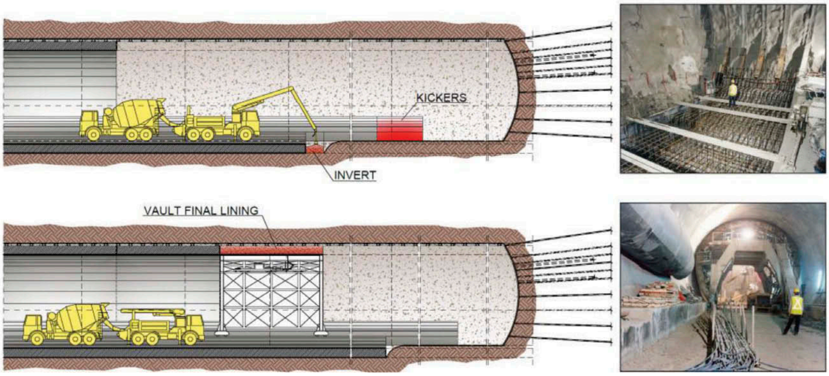

Figure 10. Invert casting & final lining.

The analysis of the monitoring data (mainly geological face mapping and extrusion-convergence measurements) will allow to confirm the predicted section type and regulate the intensity of the interventions and of the executive phases (such as, excavation step, distance from the face for invert casting and final lining casting).

5.2 *The evidence of the risk reduction*

The analysis of some specific work phases (Figure 11), clearly explain the risk reduction reached by the application of the concepts previously explained (cf. chapter 4). The full-face excavation method leads to operate in a wide working space using large and powerful equipment.

Face or cavity reinforcement installation is performed by a tunnel drilling machinery, the geometry of this equipment, characterised by two cradles that house the system of sliding blocks and telescopic arms, lets the worker operating far from the face in a safety area. Furthermore, each of the single drilling arms is fully independent, driven by two separated power and remote-control unit.

Steel arches are installed by using an excavator equipped the three arms handlers.

Scaling is always performed by hydraulic hammer and *concrete is sprayed* by shotcrete manipulator.

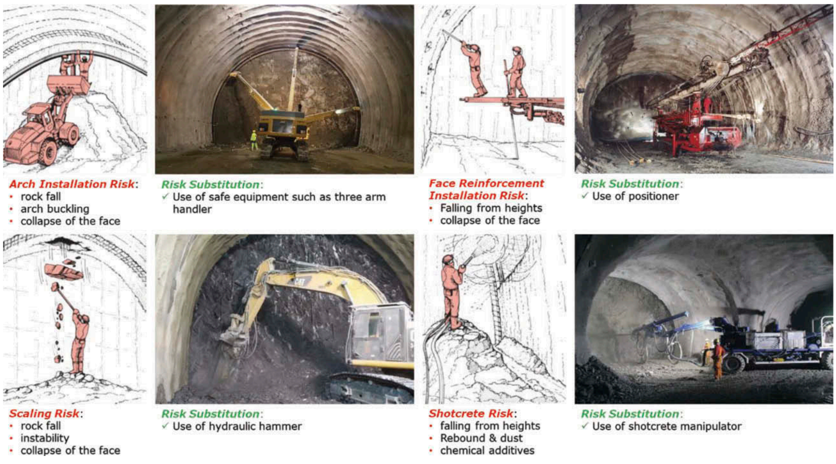

Figure 11. Example of risk reduction trough the application of a full-face excavation method.

6 CONCLUSION

The management of the risks associated with tunneling work follows a systematic process, which involves identifying hazards, assessing and controlling risks. Estimates of uncertainties and risks of the construction process are essential information for decision-making in infrastructure projects.

The risk is inherent all engineering applications and tunnel construction, is also prone to several hazards originating from different sources. In the early design and tender and contract negotiation phases, certain risks may be transferred, either contractually or through insurance, others may be retained and some risks can be eliminated and/or mitigated. In the construction phase, possibilities of risk transfer are minimal and the most advantageous strategy for both owner and contractor is to reduce the severity of as many risks as possible through the planning and implementation of risk eliminating and/or risk mitigating initiatives.

Safety Issue has been considered an important topic since a long time and around the world. The Occupational Health and Safety department of the Regions Emilia Romagna and Tuscany in Italy, developed the Interregional Rules based on Italian Experience referred to more than 150 km of tunnel bored using full-face excavation method. Each NIR is a monothematic technical treatise containing design, construction, organizational, technological and operational solutions developed achieving the highest safety levels. The Rules consider only full-face excavation method, this design choice is supported by previous experience in which this solution proved to be successful compared to the "partial excavation".

Main advantages of the full-face excavation are related to the industrialization of the work phases. There are always few workers moving into the tunnel, with a limited number but powerful machines and equipment to be used, with a clear sequence of operations. There is never a superposition of different kind of interventions or operations. There is a direct relationship between the number of workers and of the machinery and safety: the less they are, the greater is the safety.

The full-face excavation method has a lot of benefits in term of safety but the concrete prelining sprayed on the face and on the excavated portion of the cavity has a fundamental function preventing rock fall and local instability of the face and of the cavity. The huge dimension of the face (varying from 130 m^2 to 230 m^2) requires this procedure as the first safety provision despite to the fact the area close to the face is forbidden to man works and operations, because the best way to protect the worker is risk elimination.

Construction engineering and safety go hand in hand and everybody must come back home safely at the end of their shift.

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