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Health & Safety in Underground Space
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"Historical evolution of Health & Safety issues in tunnelling".

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Presentation summary

> This presentation will focus on the past 40 - 50 years which have probably seen the greatest changes in health and safety in tunnelling.
> Prior to that tunnelling was generally a high risk manual operation, depending on the strength and stamina of large numbers of men working in unsafe and unhealthy conditions underground.
> A number of significant changes past, present and future will be highlighted in this presentation but my time is limited.

Terminology

> This presentation will follow International Tunnelling Association terminology.

> Mechanised tunnelling – use of TBMs for excavation.
> Conventional tunnelling – excavation by means other than TBMs.

> Normally two ground types are considered in tunnelling,
> Soft ground,
> Hard rock.

Changes in H&S philosophy in recent decades

- There has been a major change in the perception of acceptable risk by society in all aspects of life.
  - Smoking was fashionable but now is no longer widely acceptable on health grounds.
- Society expects the prevention/avoidance of death and injury due to industrial incidents to much greater extent.
- Professional engineers now recognise they have much more responsibility for health and safety both through design and on site.
- Penalties for breach of H&S law are increasing.

Changes in H&S philosophy in recent decades

- Prescriptive health and safety legislation is being replaced by risk-based legislation.
- Occupational health is being recognised as a major source of death and illness in construction.
- Mental health is an aspect of occupational health which to date has largely been ignored but that is changing.
- Welfare is important for good industrial relations and if good occupational health outcomes are to be achieved.

Changes in European regulatory environment

- Major changes in H&S have been driven by European legislation.
- There has been growing intervention by the EU both directly and indirectly in health and safety.
- Framework Directive 89/391/EEC introduced "measures to encourage improvements in the safety and health of workers at work".
  - It also introduced several "individual directives" on specific topics some of which are particularly relevant to tunnelling.

Framework Directive

> The Directive is of fundamental importance as it laid down general principles concerning the prevention and protection of workers against occupational accidents and diseases.
  - "Workers' obligations shall not affect the principle of the responsibility of the employer".

> It also contained principles concerning the assessment of risks, the elimination of risks and accident factors, the informing, consultation and balanced participation and training of workers and their representatives.

Individual Directives

> Individual Directives affecting construction and tunnelling include directives on topics such as:-

- Use of work equipment
- Use of Personal Protective Equipment
- Temporary or mobile construction sites
- Manual handling
- Work in potentially explosive atmospheres
- Noise
- Vibration

Machinery Directive

- The Machinery Directive 89/392/EEC was published in 1989 at the same time as the Framework Directive.
- The current Machinery Directive is 2006/42/EC.
- Its purpose remains to remove barriers to trade through the establishment of common standards for machinery safety throughout Europe.
- The Machinery Directive sets out essential safety requirements (ESRs) for machinery and applies to manufacturers not users.

Machinery Directive

- All machinery placed on the European market must conform with the ESRs.
- Conformity with the ESRs is normally most easily demonstrated by a "declaration of conformity" by the manufacturer with a relevant harmonised European (CEN) standard.
- This makes harmonised standards quasi-mandatory.
- Although it was intended as an economic measure it has led to an increasing level of safety

Conformity with the ESRs

> Numerous CEN standards apply directly or indirectly to machinery used in tunnelling.

> The most relevant for mechanised tunnelling are
- EN 16191 – TBM safety
- EN 12110 – Airlocks

> And for conventional tunnelling
- EN 12111 - roadheaders
- EN 474 – earthmoving machinery

Conformity with the ESRs

- EN 16191:2014 was first published as EN 12336 applying to soft ground shield machines with EN 815 applying to hard rock (unshielded) TBMs.
- Increasing similarities in machine design now allows all TBMs to be covered by one standard.

Explosive atmospheres

- The ”ATEX” Directive 2014/34/EU applies to equipment and protective systems intended for use in potentially explosive atmospheres.
- The directive defines the essential health and safety requirements and conformity assessment procedures to ensure safety in potentially explosive atmospheres for products placed on the EU market.
- There is also an individual directive addressing the safety and health protection of workers potentially at risk from explosive atmospheres.

Changes in practical health and safety

- The single biggest impact on health and safety in tunnelling over the past 50 years has been the increase in **mechanisation**.
- Developments have included an increase in the size, power and sophistication of TBMs.
- Consequently deeper, larger and more technically challenging tunnels have been built.
- Mechanisation also has reduced the amount of conventional tunnelling across all diameters and ground types.

Mechanisation

Mechanisation has taken us from hand excavation with health risks such as manual handling, heat, noise and vibration to mechanical excavation …

Mechanisation

… and from TBMs of this size (~3.5m diameter) to this size (~17.5m diameter).

Manual handling and other health risks now replaced by complex machinery safety risks.

Mechanisation

Mechanisation in the 1990s replaced manual erection of lining by the use of lining erectors

Mechanisation

- Mechanisation has again removed the risk of musculo-skeletal injury and replaced it by the risk of mechanical impact.
- Work at height risk has also been introduced.

Mechanisation

In rock we have gone from hand drilling to mechanised drilling and to TBMs

Overall effect of mechanisation on H&S

- Mechanisation has resulted in a significant reduction in manual work with a corresponding increase in mechanical excavation.
- As a result the risk profile has changed from health with some safety risks in conventional tunnelling, to mainly safety risks with residual health risks in mechanised tunnelling.
- The numbers at risk have also changed as mechanisation requires fewer miners for the same output.

Remote control, automation and AI

- > Remote control, automation and artificial intelligence represent the next stage in mechanisation.
- > I discussed these issues in my lecture to the ITA CET training course run in conjunction with WTC 2019 in Naples.

Remote control, automation and AI

> It has some applications such as cutter changing.

> However I concluded

- greater use of remote control was likely.
- extensive use of automation and artificial intelligence in tunnelling would result in a number of complex safety issues.
- large scale automation was unlikely to be cost effective in the foreseeable future.

Mechanisation – pipejacking

- Removes the need for hand excavation in small diameters.
- Removes the need for lining erection in small diameters.
- Allows remote control from the surface.
- Leads to a number of health and safety benefits.

Conventional tunnelling plant

- This is one area in which standardisation has yet to take effect.
- Need for a standard "Additional requirements for surface construction plant taken underground".

Conventional tunnelling plant

> There are risk mitigation measures required specific to the underground environment.

- Fire suppression
- HFDU fluids
- Lights
- Ram and hose protection
- Ventilated cab
- Single point lifting
- Low emissions

Work in compressed air

- As tunnels get deeper, more excavation is required below the water table.
- Historically, excavation below the water table involved the application of compressed air to the tunnel, with large numbers of men exposed.
- Work in compressed air has been undertaken since the mid 19th century.
- Working techniques changed little for almost 150 years, although knowledge of the medical issues – decompresion along with decompression illness and its treatment - did improve.

Work in compressed air

- With mechanisation the number of exposures have been reduced.
  - 2nd Dartford Road Tunnel opened 1980 – hand excavation, ~120000 exposures.
  - "High Speed 1" opened 2003, ~120 exposures. 2 tunnels, TBM driven. Same diameter, length, ground conditions.
- The benefits of oxygen assisted decompression had been known for much of the 20th century but had been ignored.
- Only towards the end of the century did oxygen decompression become accepted in tunnelling.

Work in compressed air

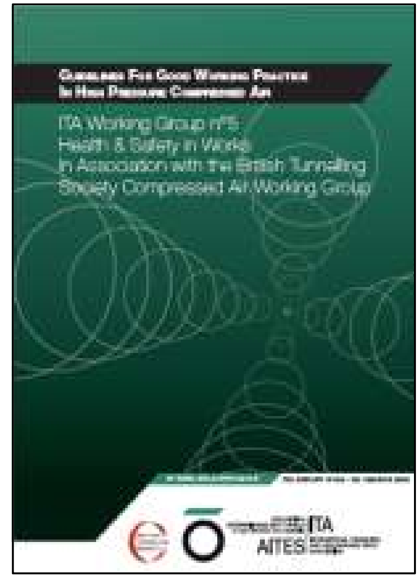
We have moved from traditional in-tunnel airlocks to TBM airlocks

Work in compressed air

- As tunnels (and shafts) get deeper higher pressures are required for ground stabilisation.
- Historically, air non-saturation exposures were undertaken and pressures were limited by law to 3 – 4 bar.

High pressure compressed air work

- > In the past 10 years, tunnels requiring pressures of up to 10 – 15 bar have been excavated.
- > This has required the use of advanced hyperbaric techniques commonly used in the offshore diving industry.



High pressure compressed air

> These techniques include the use of non-air breathing mixtures, saturation exposures and transfer under pressure.

> Despite the high pressures, mixed gas and saturation exposures result in significantly fewer decompression problems.

Revision of EN 16191 – TBM safety

> Originally published in 2005, the current 2014 edition covers both soft ground and hard rock TBMs and is being revised and extended to take account of current developments in TBMs along with omissions in the text.

> Developments to be included
  - Robotic tool changing, hollow spoke cutterheads, high pressure compressed air work.

> Omissions
  - Safety of slurry circuits

Revision of EN 12110 – airlock safety

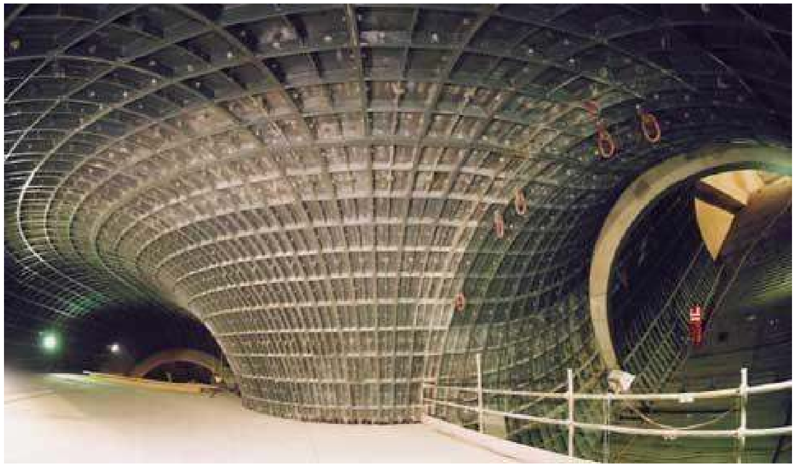
- EN 12110 was first published as a harmonised standard in 2002.
- Revised in 2014 it is now being revised again and split into two parts – Part 1 applying to air locks for exposures using air as the pressurising and breathing medium, along with oxygen decompression. Part 2 applying to additional requirements for mixed gas and saturation, along with TUP shuttles.
- It covers the design, testing, equipping of airlocks.

Revision of EN 12110

- Historically bulkhead were inserted into the tunnel lining to form airlocks.
- With mechanisation, air locks became part of TBMs where due to limitations on space, lock dimensions were reduced.
- Perhaps the most overt benefit of EN 12110 has been in setting minimum dimensions for personnel locks.

Sprayed concrete linings

> Along with increased mechanisation, the development of sophisticated finite element design methods and fibre reinforced concrete as a material has driven the use of spray applied linings including their use for complex tunnel shapes.



Sprayed concrete lining

> Advantages
  - Cost effective
  - Flexible

> Disadvantages
  - Needs competent engineering input
  - Requires good quality workmanship

> Risks - dust and ground collapse

Atmospheric monitoring

- Atmospheric contamination has resulted in fatalities from oxygen deficiency, methane and the presence of toxic gaseous contaminants.
- Advances in monitoring technology have made such fatalities preventable.
- Flame safety lamps from the 19th and early 20th century have been confined to history.
- Electronic atmospheric monitoring equipment is now available to detect all gaseous contaminants found in tunnelling.

Atmospheric monitoring

- Use of a fixed monitoring installation is the preferred technique
  - Linked to tunnel data systems
- Supplement with portable instruments as necessary

Atmospheric contamination

> Dust inhalation is a major cause of respiratory ill health.
> Dust occurs as inhalable dust or respirable dust.
> Respirable dust from soil or rock contains crystalline silica.
> Dust is not a particular risk in mechanised soft ground tunnelling.
  - Slurry TBMs capture any harmful dust in the slurry
  - EPB machines produce conditioned spoil which does not release large amounts of dust.

Atmospheric contamination

- Dust is a major hazard in conventional tunnelling.
- It is an outcome of sprayed concrete linings in tunnelling.
- It is also an outcome of both mechanised and conventional tunnelling in hard rock.
  - May require the use of slurry TBMs in rock in the future
  - Asbestos occurs naturally in some Alpine rocks in Europe.
- Respirable crystalline silica is now classified as a human carcinogen in Europe.

Atmospheric contamination

- Reduction in exposure should be achieved in accordance with the requirements of 89/391/EEC.
- This requires by preference, reduction in emissions at source
  - through mix design and better spraying techniques.
  - through suppression and capture in rock excavation.
- Respirable crystalline silica is now classified as a human carcinogen.
- Consequently containment and prevention of secondary exposure is required.
  - Extraction ventilation rather than forced ventilation.

Atmospheric contamination

> Electronic gas monitoring equipment depends on chemical reactions and cannot be used for dust.

> Dust being a particulate is therefore difficult to monitor in real time.

> Historically, dust was a factory problem and was measured by use of a filter pump which gave results in days.

- Based on an 8 hour average value

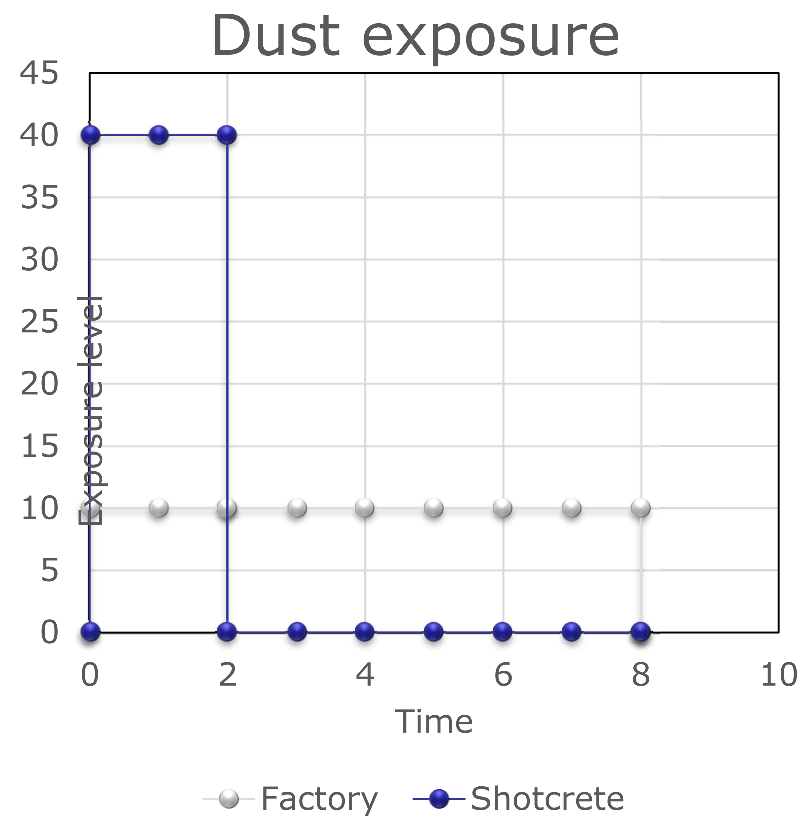
> With technological advance, laser light scattering technology is now available to monitor particles.

Real time monitoring

> Real time monitoring now a reality for respirable dust.
> Inhalable dust monitoring requires recalibration of instrument.
> RCS monitoring being developed.
> This is a major advance in dust exposure control.

Exposure comparison – SCL v factory

- Factory exposure v SCL exposure
- Both exposures equate to 10 mg/m^3 over 8 hours
- Control should be based on 15 minute average levels not 8-hour averages.



Diesel exhaust emissions

> There is an increased awareness of the harmful effects of diesel engine exhaust emissions
  - Emissions contain both gases CO_x and NO_x and carcinogenic particulates.

> Directive 2017/164/EU "Indicative occupational exposure limit values" sets out new and more stringent exposure limits on COx and NOx to come into force in the underground environment in 2023.

Diesel exhaust emissions

> Till recently the exhaust gases could be monitored but not the particulates.

> With advances in particulate monitoring technology diesel exhaust particulates can now be monitored.

> However exposure limits are still being discussed.

Diesel Particulate Matter

- Diesel particulate matter - real time monitoring based on 15 min averages
  - Must be able to differentiate between DPM and mineral dust
  - A possible limit is 100 µg/m^3 ?

Self rescuers

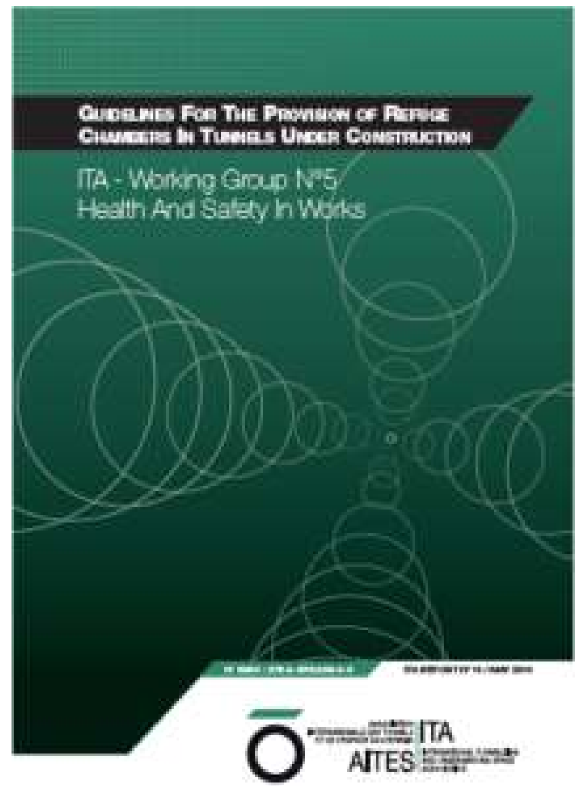
- Self rescuers provide life support for a person escaping from a fire or atmospheric contamination event in a tunnel.
- In UK filter self-rescuers were first introduced on Channel Tunnel in 1987

Self rescuers

- Filter self rescuers provide only limited protection.
  - carbon monoxide and dust only
- Since the early 1990s oxygen self rescuers have been a standard requirement in tunnelling
  - protection against all contaminants

Refuge chambers

> Places of relative safety underground.
> The provision of refuge chambers has mainly come about over the past 10 years.
> EN 16191:2014 requires their provision “where shown necessary by the tunnel project risk assessment”



Refuge chambers

- > ITA WG5 has produced guidance on the use of chambers in 2014 which was updated in 2018.
- > Chambers can operate in "externally supported" mode with life support services from the tunnel or in "stand alone" mode for at least 24 hours

Resurgence in use of battery power

- Battery power has long been used in tunnelling.
- Eliminates exhaust emissions.
- “Lithium” batteries now replacing lead-acid batteries
  - High power capacity
  - Quick charging
  - Fire safety issues

Resurgence in use of battery power

- "Lithium" batteries represent a range of battery technologies incorporating heavy metals, lithium and fluorine compounds.
- Introduces risk of overheating and fire, releasing toxic fumes.

Conclusions

- Numerous changes in health and safety have taken place over the past 50 years in tunnelling.
- Mechanisation has had the greatest impact.
- It has led to changes in the risk profile as well as to an overall improvement in standards.
- Technological advances have also led to health and safety improvements.
- Further changes and improvements will occur in the future.

Thanks for inviting me to speak
and
for your attention