Tunnel Spoil Handling, Treatment and Disposal Options from a Global Perspective

ITA Working Group 14
Mechanized Tunnelling – Task Group 4

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1 >> Abstract

More and more tunnels are being excavated every year, producing millions of cubic metres of rock, soil and water to be disposed of within legal and sustainably sensitive approaches. To date, there is no, consolidated guideline available to suggest how this may be achieved in an environmentally and socially responsible manner. This document will strive to suggest what is and is not suitable and further describe using numerous Case Studies, what can be done as practical mitigations.

Several Case Studies and Project Examples are presented that describe novel methods for handling, treating and disposing of products of excavation; i.e. solids, liquids, dust and gases within the available technologies and site restrictions. In several cases, the combination of ground and groundwater conditions were so egregious that very creative site-specific means and equipment were developed and successfully implemented. In two cases, challenging subsurface conditions were complicated with the presence of methane and hydrogen sulphide gas.

Legal and regional spoil treatment and disposal regulations are increasingly restrictive on the use of industrial (biodegradable) chemicals frequently used for soil conditioning and ground improvement operations. The regulations have impacts that result in delays and deferments of significant and strategically important infrastructure projects around the globe.

It is expected that additional publications will follow that will provide more details and Case Studies on the national and regional requirements for tunnel spoil handling, treatment and disposal options. As described herein, this is a global challenge and one that confronts all significant tunnelling and underground construction projects.

2 >> Acknowledgements

This report presents collective work of Working Group 14 – Mechanized Tunnelling of the International Tunnelling and Underground Space Association, ITA.

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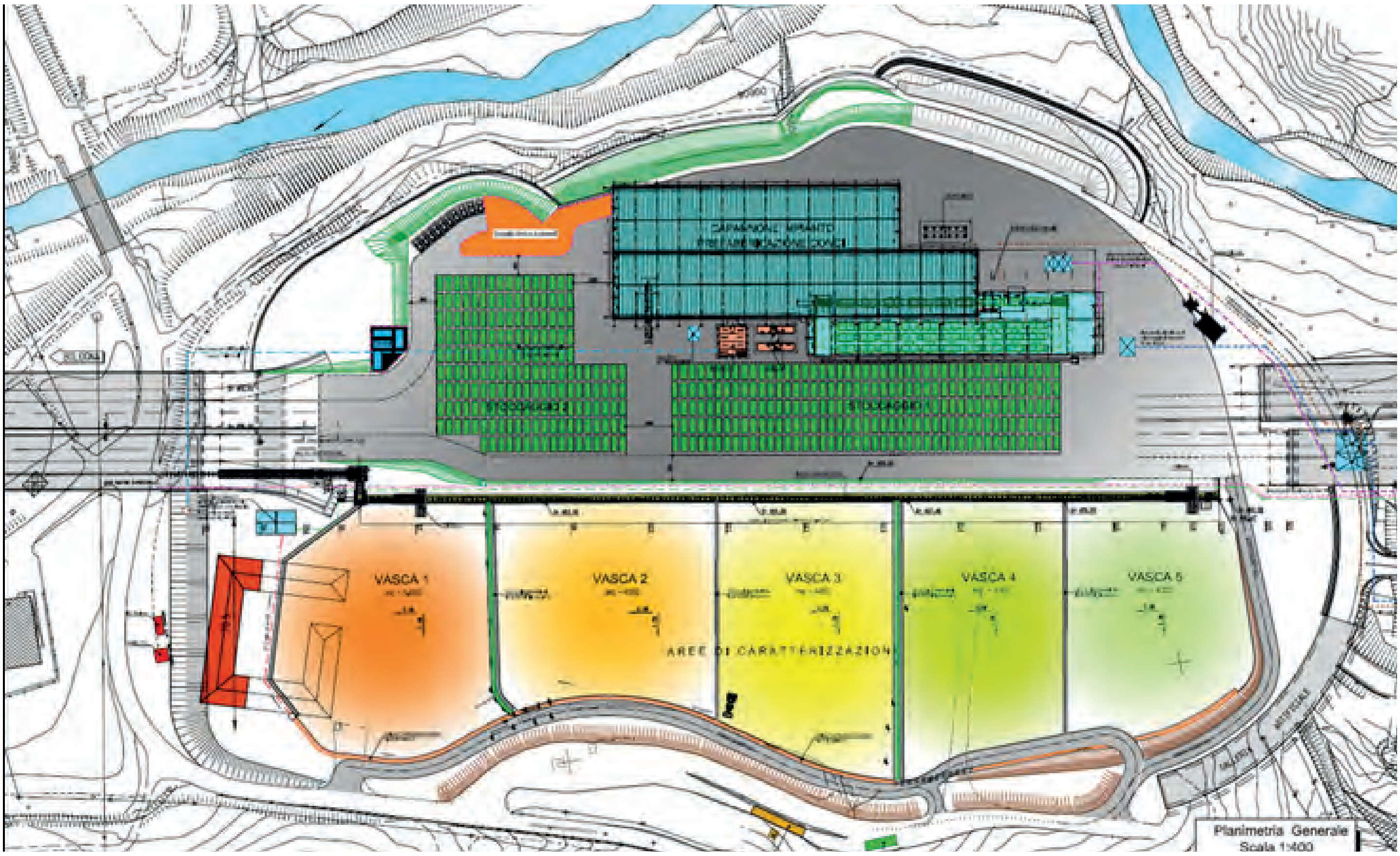
We would also like to acknowledge Working Groups 15 and 17 members, who contributed to a preceding report on a similar subject, titled, "Handling, Treatment and Disposal of Tunnel Spoil Materials" (2019). and by discussing this report over the years of preparation and provided inputs, as well as external colleagues, who provided information and a critique of the report.

In addition to the contributions from the above-listed persons, questionnaires, results from a literature study, *"Use of Excavated Material from Tunnels and Deep Excavations"*, performed by students from the Warsaw University of Technology, Poland, have been valuable for preparation of referenced portions of this report

The authors, contributors and editors would also like to acknowledge help and encouragement provided by the Secretariat of the International Tunnelling and Underground Space Association and in particular, Jan K. G. Rodhe, ITA's Peer Reviewer who provided valuable comments that were incorporated in the paper.



Sparvo Tunnel Project (Italy) – On-Site Tunnel Spoil Treatment Facility

3 >> Mission Statement for the Report

This document has been written to enhance the initial information provided in ITA Report No.21 published in April 2019 and titled *"Handling, Treatment and Disposal of Tunnel Spoil Materials"*, written jointly by Working Group 14 – Mechanized Tunnelling and Working Group 15 - Underground and the Environment.

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We content that the mission of this document is to encourage the development and construction of tunnelling projects throughout the world and to provide a guideline from which they can work to ensure that the spoil excavated throughout the tunnelling process is disposed of in a location and condition, such that it is the same as the original state from an environmental perspective.

To emphasize that whilst materials may be considered biodegradable, this is not enough. Some materials biodegrade but can be considered toxic. Both biodegradability and toxicity should be considered together when making an analysis of spoil for disposal.

To provide a document that can be referred to as a catalyst in analysing how spoil from TBMs can be disposed of in an environmentally responsible fashion. The benefit of this is quite clear. It is our responsibility to limit our environmental footprint. No blame should be appointed to our industry as being a "polluter". Any negative connotations relating to tunnelling can be limited, thereby making tunnels more attractive as an infrastructure option.

Currently, there would appear to be very few countries that give spoil disposal the necessary gravitas. This document should encourage the concept of environmentally appropriate soil disposal.

Whilst this document should be an important starting point, there are clear limitations in its application. A few such limitations are:

- Some soils contain inherent contamination that cannot be "recovered" in any treatment process. For example, oil, asbestos and industrial percolations. A recent example of this would be the Westgate tunnel in Melbourne where PFAS (Fire Fighting Foam) was discovered within the soil. This discovery led to a temporary cessation of the project until such a time as an appropriate disposal site could be found. https://apps.epa.vic.gov.au/~/media/Publications/1669%203.pdf
- Some geological conditions need more treatment pre and post tunnel excavation). An EPB cannot efficiently penetrate gravels without significant use of chemical additives. These chemicals can, however, be better considered.
- Slurry-faced TBMs often need specific chemicals to handle more difficult geological conditions.
- This is the second document on this specific topic prepared by the ITA Working Groups. Consequently, there may be extremely pertinent information out there that we have missed. We are sure there will be a future need for revision. There have been a few projects in Australia where the disposal of the soil has been specified responsibly, however, these Projects are unable to share the information as it is considered sensitive.

3.1 INFORMATION USED IN PREPARING THIS REPORT

The primary persons involved in the preparation of this document are members of ITA Working Group 14 – Mechanized Tunnelling. This is a group of industry specialists and as members of ITA, convene annually (and more frequently) with the goal of producing documentation deemed to be helpful to the global mechanised tunnelling industry.

To compile the report, we asked the international tunnelling and underground construction industry for data, regulations and narrative contributions to compile and consolidate and to contribute Case Study examples of challenging, yet successful projects. Almost all the documentation received to date relates to construction and ground treatment chemicals and waste regulations that are directly and indirectly related to all tunnel spoil materials (i.e. solids, liquids and gases). On rare occasions, state and local waste material regulations were directed or dedicated to tunnel spoils.

The enclosed Case Studies were found to be very revealing in that many utilized creative methods for handling, treating and disposing of tunnel spoil materials beginning early in the life cycle of the project. Table 1 below provides a brief overview of the Case Studies and Project Examples as well as the tunnel excavation spoil materials encountered.

Many reference documents were reviewed in the compilation of this report. These are referenced in the Appendices and are available through listed the associated websites using the referenced file names. All images, figures and tables are the work of the report authors, contributor and editors unless cited otherwise.

3.2 INTENDED AUDIENCE FOR THIS REPORT

The global tunnelling and underground construction industry should make considerable use of this report (as well as successive revisions). The handling, treatment and proper disposal of tunnel spoil materials is a significant global challenge and especially in consideration of progressively stricter environmental controls on the use of chemical additives and accessibility of practical disposal sites needed for tunnelling operations. The intended audience for this report, therefore, includes many diverse groups of individuals engaged both directly and indirectly with the planning, design and construction of tunnels, caverns and underground facilities as well as others engaged in research for potential reuses, repurposing and reprocessing all forms of tunnel spoil materials.

- Specification Writers
- Clients, Contractors, and subcontractors, etc.
- Educators
- Researchers in systems and material sciences
- Project Planners
- Program Managers
- Project Managers
- Plant and Equipment Designers
- Material and Equipment Suppliers

Figure 1 below illustrates a typical hard rock TBM in the course of tunnel construction; for the Deer Island Effluent Outfall Tunnel Project in Boston, Massachusetts, USA.

3 >> Mission Statement for the Report

ITEM	PROJECT	LOCATION	EXCAVATION METHOD	PRIMARY SPOIL MATERIALS						
				ROCK	SOIL	WATER	GAS	DUST	POLs	CONT't
1	Santa Lucia Tunnel Project	Italy	EPB		•		•			
2	Arrowhead Tunnels Project	USA	HR/slurry	•	♦	•				♦
3	OARS Tunnel Project	***USA***	***HR/slurry***	•		•	♦			
4	Second Avenue Subway	USA	D & B	•				•		
5	Sparvo Tunnel Project	Italy	EPB		•		•			
6	Los Angeles Metro	USA	EPB		•		•		•	♦
7	Eagle Mountain Tunnel	Canada	HR + Slurry	•	•	♦	•	•		
8	Cross Rail Tunnels	**UK**	**EPB**		•		•			

Table 1: Tunnel Project Case Studies and Project Examples for Spoil Materials
General summary of tunnel and underground construction Case Studies and Project Examples that address various tunnel excavation spoil materials encountered, treated and disposed of (included repurposing and remanufacturing options).

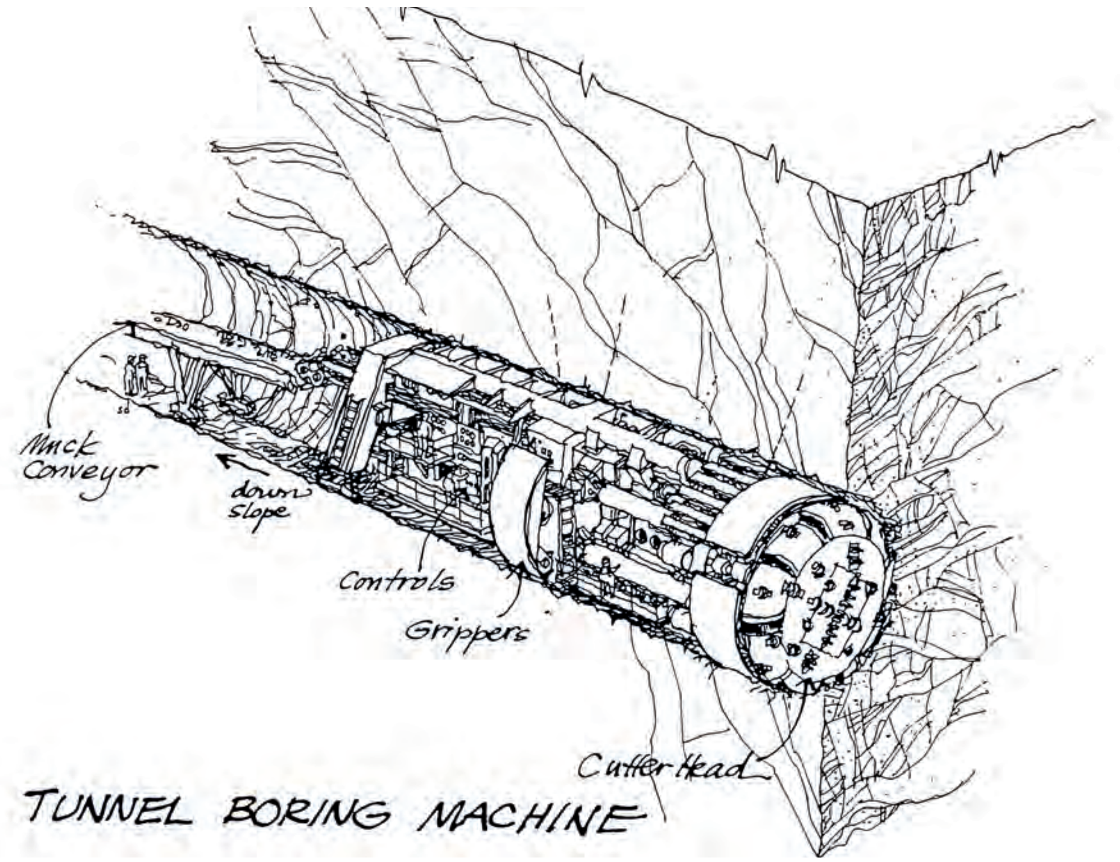


Figure 1 : Typical Hard Rock Tunnel Boring Machine Operation
Isometric view of a Tunnel Boring Machine (TBM) operating in hard rock strata, using a conveyor for spoil (muck) transport. A TBM may be connected to an extensible tunnel conveyor or discharge into tunnel muck cars for rail haulage to a portal or shaft and vertical hoisting equipment.

4 >> Introduction

The report together with cited references, reading lists and Appendices is intended to provide a global perspective of the increasingly more difficult task to handle, treat and dispose of all tunnel spoil materials, in areas where environmental and safety controls dominate the design and construction aspects of the work. Indeed, some critically important project planning elements include the sampling, testing and recommendations for proposed mitigation measures related to tunnel spoil materials, long before any excavation has begun. Additionally, essential Health and Safety related material sampling and testing is required to fully assess gas(es), minerals and chemical content of the anticipated tunnel excavation spoil materials.

Approvals for some tunnelling projects are largely conditional on successful pre-construction material and chemical testing with additional statute-driven and permit required progress reporting and testing criteria.

Activities and corresponding formal approvals from regulatory agencies may be needed for the following, for example (but not in all cases).

- Ongoing research in material sciences
- Long-term plan for spoil treatment and disposal

It has been the writers' experience and through considerable research for this paper, that we have found that chemical processing methods for the spoil (solids and liquids) are rapidly changing. Additionally, there are more regulations and strict enforcement on the treatment and final disposal of all tunnel spoils including naturally occurring gas (i.e. methane), solids (i.e. asbestos) and ground improvement materials (e.g. cementitious and chemicals used in grouting operations) that occasionally spill into the surrounding construction environment.

Projects are often held in abeyance (or substantially deferred) in various design and development stages while waiting for formal approvals related to the treatment and final disposal of spoil materials. This may include beneficial use and repurposing; and in some cases, remanufacturing into bricks and concrete aggregates, as two potential examples. Additional issues to satisfactorily resolve in the design stage include those related to acute Health and Safety materials (i.e. gas, silica and asbestos) as well as environmental and social (material transport, pH levels and chemical content).

Several materials which in the past were not so strictly controlled or even considered hazardous, are now considered in many locations as "regulated and controlled substances" and require measurement and documentation for proper disposal.

- Fly ash
- Acidic Rock Drainage (ARD)
- Metal Leaching (ML)
- Salt
- pH levels
- Trace asbestos
- Dust particles (silica)
- Toxic and carcinogenic materials
- Gases (combustible, flammable, corrosive, explosive and poisonous).

This tunnel spoil report addresses many aspects of both mechanically and conventionally excavated tunnels as the resulting "products of excavation". Indeed, the preferred excavation method has significant impacts on the types and quantities of tunnel spoil materials needing treatment and final disposal options. This is not a new challenge and in one way or another, has confronted all tunnelling and underground construction projects; "what to do with the spoil material and groundwater". Take for example the large quantities of the tunnel and underground cavern spoil materials generated from New York City's initial subway construction in the 1900 to 1905 era. Much of this was deliberately hauled over land and water to New York Harbour and placed in a manner to enlarge the existing Governors Island. Excavation approaches included substantial open cut and hard rock tunnelling by drill and blast methods. Spoil haulage was accomplished for the most part with horse-drawn wagons. Please refer to Figures 2 and 3 below for historical and modern era aerial views of the original and expanded Governors Island.

4.1 GOVERNORS ISLAND, NEW YORK CITY HARBOUR

Physically, the Island changed greatly during the early 20th century. Using rocks and dirt from the excavation of the Lexington Avenue Subway and dredge from New York Harbour, the Army Corps of Engineers supervised the deposit of 3,662,600 m^3 (4,787,000 yd^3) of fill on the south side of Governors Island. This fill was used to add 42 hectares (103 acres) of flat, treeless land, increasing the size of the Island to 70 hectares (172 acres) by 1912.

Based on reports and records of the day, the following has been extracted in relation to the handling. treatment and final disposition of the tunnel and excavation spoil materials originating from a portion of the first phase New York City's subway construction.

On March 3, 1901, $260,000 was appropriated toward the enlargement of Governors Island and for construction of storehouses and other buildings. An additional grant of land under water was requested by the legislature of the State of New York, which led to an increased amount available for enlargement of $162,259.90.

While there were cost overruns and schedule delays in construction and enlargement, the project was able to keep the cost of filling for the enlarged area under control due to the building of the Rapid Transit Subway in New York City. Construction of the Rapid Transit Subway, the first in New York City, officially began on March 24, 1900, and was completed late October 1904. During the height of construction, over 7,770 men were employed.

The large quantities of stone excavated had to be disposed of. The Corps of Engineers anticipated needing 3,662,600 m^3 (4,787,000 yd^3) of fill behind a 2,200m (7,219 feet) long seawall at Governors Island. When contractors were able to offer excavation material from subway construction, the federal government was pleased to benefit from the availability. When the proposals were reviewed to determine who would be the contractor for the rip-rap bulkhead at Governors Island the lowest bid received was thirty-five cents, the next bid being forty-seven cents. The prices represented; …..“only the cost of delivering and

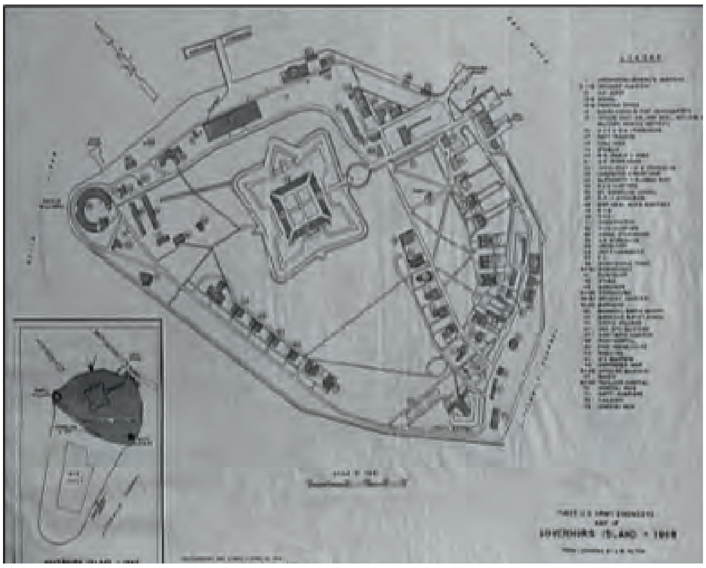


Figure 2: Governors Island – New York City, 1800's
Early map of Governors Island located in New York City Harbour showing fortifications.

Figure 3: Governors Island – New York City, present
Present day aerial view of Governors Island located in New York City Harbour showing expansion.

placing the stone. It is quarried in the Subway Rapid Transit Excavations and must be removed. This condition will last only while rock is being excavated in large quantities – probably a year longer."

The New York Times posed the question in a headline "What has become of all the dirt taken from the Subway." The answer reveals how various building projects around the New York Harbor benefited from recycling gneiss excavated for the subway, including filling the bay between Bedloe's Island and the Jersey shore. While people were aware of the remarkable feat of American engineering of the subway,

"….. few knew of the men who have been moving the dirt and stone with wagon, derrick, viaduct, tug, and scow from under the feet of New York. Uncle Sam himself has used many hundred thousand cubic yards of subway stone and dirt in his Herculean labor of increasing the size of Governors Island from sixty acres to a hundred and fifty-two acres. This means that the foundation has been laid for an addition, one-half mile in diameter, to the historic island, extending out into Butttermilk Channel and to the southwest."

4.2 MODERN ERA CHALLENGES FOR TUNNEL SPOIL DISPOSAL

The repurposing and/or remanufacturing of tunnel spoil material has challenged tunnel designers and builders for some time. In the earliest of time, solid spoil material was hauled and disposed as landfills. Liquid spoil was rarely treated and often disposed into local streams and sewer systems. Now with strict regulations (and enforcement) in place, all forms of tunnel spoil material required cared and deliberate advance planning the decision-making for treatment and disposal to satisfy environmental and social goals in additional to statute-driven regulations. Modern treatment (i.e. chemical, thermodynamic and mechanical methods) result in many secondary and repurposed materials. Please see the flow chart in Figure 4 for a graphic summary of tunnel spoil production, handling, treatment and final disposal.

4.3 LEGAL AND REGULATORY REQUIREMENTS

The Case Studies and Project Examples enclosed in this report make reference to many legal and regulatory requirements. This is not intended to be an all-inclusive list from the referenced countries and projects. Additionally, many current laws and formal regulations are subject to modification(s) without notice. Interpretation and enforcement of applicable laws and regulations affecting tunnel spoil materials are highly variable and subject to site-specific conditions and local practices.

Depending on the size, location and characteristics of a tunnel project, incentives starting in the concept development and design stage would be a positive step to minimize and avoid, "not in my backyard" mentality and therefore, resistance to a project without fully realizing the benefits. A well-thought-out composite plan for spoil material utilization should be clearly part of an all-encompassing Project Execution Plan and not left to chance (or opportunity) over the course of construction.

Often economic incentives or an emerging opportunity for all aspects of spoil material handling, treatment and final disposal options should be seriously considered early in the project lift cycle. On a recent project in Switzerland for example, EPB tunnel spoil was transported by belt conveyor in the tunnel, then loaded onto dedicated hopper cars and hauled on the national railway system approximately 100km to a dis-used rock quarry for backfilling as an environmentally sensitive and cost-effective solution, concurrently, satisfying many social goals from an early stage of the project.

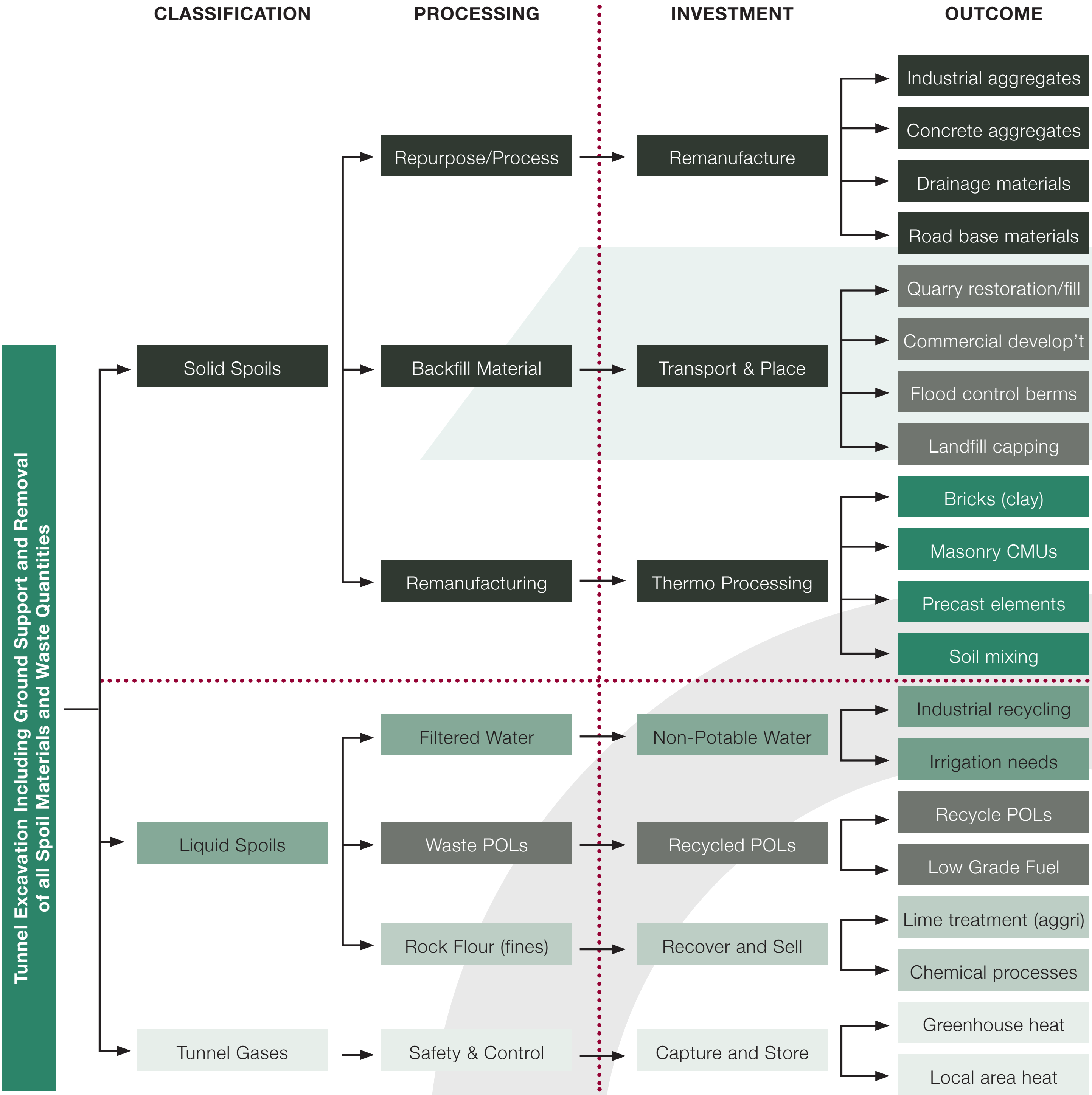


Figure 4: Tunnel Spoil Classifications – Generalized Process Flow Chart for Tunnel Spoil Disposition
Bulk (dry, slurry (wet) and gaseous) tunnel spoil classifications and process flow chart showing possible final disposition(s) of typical tunnel spoil materials including waste, recycling and potential remanufacturing and repurposing options.

4.4 TUNNEL SPOIL MATERIALS

In general terms, tunnel spoil material is largely considered to be products of the excavation, by whatever means performed. Indeed, the products of the excavation can be highly variable depending on geological conditions, material handling methods and treatment process. Groundwater and gasses are also products of tunnel excavation and must be suitably handled to achieve successful and safe excavation.

There are also several other additional products of tunnel excavation that while smaller and less contentious in volumes, need attention and inclusion in the overall tunnel spoil management program. Consider the following for example and as listed in the flow chart below in Table 2.

Figure 5 illustrates a global material process flow chart for both incoming and outgoing commodities needed for successful and safe tunnel construction.

This report addresses virtually all products of tunnel excavation, but without exhaustive detail that is often included in the published reports. Please refer to Section 14 – Reference Documents and Additional Reading Materials. Many of the tunnel spoil materials, i.e. gas and groundwater encountered have had a major impact on the initial design, construction planning and approach as well as construction execution.

In some cases, where substantial quantities of methane (CH_4) and/or hydrogen sulphide (H_2S) were anticipated, (i.e. the Sparvo Tunnel in Italy and the Los Angeles Metro tunnels in the United States), the entire tunnelling method, approach, equipment and intensive safety systems were heavily influenced and redesigned to mitigate threats and potentially severe safety issues. These were not insignificant undertakings; to successfully and safely excavate and line the tunnels both for construction needs, but also for long-term operation and performance of the facilities within the adverse ground conditions.

In the case where excess groundwater (also considered as a tunnel spoil material) was anticipated during construction and afterwards, during operation of the tunnel and related facilities, the entire tunnelling approach, methods, equipment, materials and safety systems were substantially modified from those traditionally used in «dry» tunnel conditions. These changes were not easily made with adjustments often requiring complete overhaul of the original tunnel spoil handling and treatment equipment. Project examples include the following projects each of which were heavily impacted and substantially overwhelmed with excess groundwater inflows.

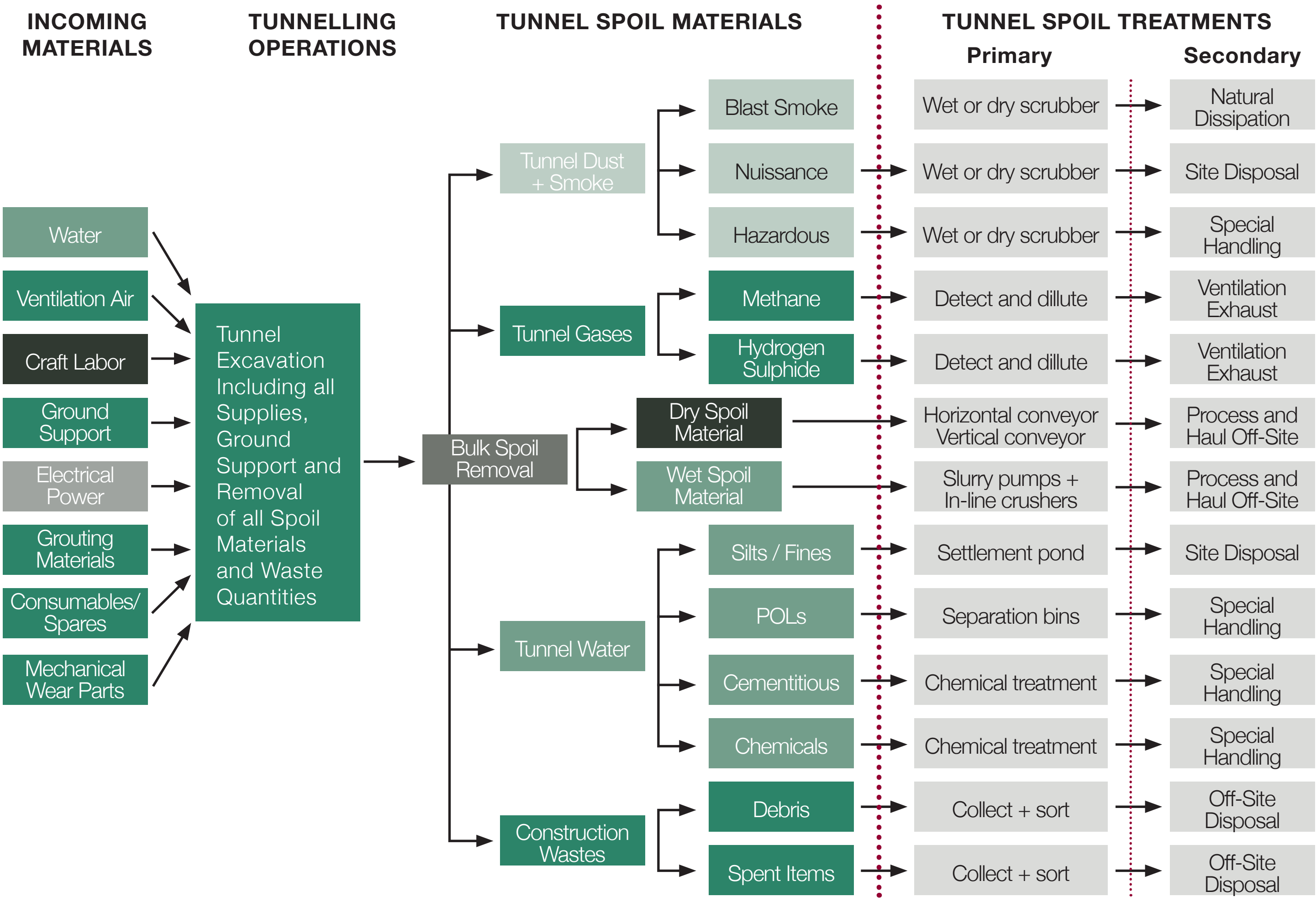


Figure 5 : Tunnel Materials – Incoming and Outgoing; Generalized Process Flow Chart

Generalized illustration of the nature of incoming and outgoing materials, services and labor needed for tunnel construction. Ultimately all will be consumed into the work or discharged from the tunnel for final disposition including waste, recycling and potential remanufacturing and repurposing options.

Generalized summary of the frequently occurring substances in excavation tunnel spoils without regard to the excavation method(s) as well as any particulars of the geological formation. Please note that many of these occurrences may also be encountered in site preparation and foundation work scopes.

ITEM	MATERIAL DESCRIPTION	TUNNEL EXCAVATION METHODS					
		MECHANICAL		CONVENTIONAL		SEM	
		Hard Rock	Soft Ground	Hard Rock	Soft Ground	Soft Rock	Soft Ground
A	**Groundwater**						
1	Fresh	●	●	●	●	●	●
2	Contaminated (any chemical)	◆	●	◆	●	●	●
3	Saline	◆	◆	◆	◆	◆	◆
4	Chemical residues (all types)	◆	◆	◆	◆	◆	◆
B	**Gases**						
1	Methane	◆	◆	◆	◆	◆	◆
2	Hydrogen Sulphide	◆	◆	◆	◆	◆	◆
3	Gasoline vapours	∇	∇	∇	∇	∇	∇
4	Hydrocarbon vapours	∇	∇	∇	∇	∇	∇
5	Dry cleaning fluid (tetrachloroethylene)	∇	∇	∇	∇	∇	∇
C	**Dust**						
1	Rock flour	●		●		◆	
D	**Odours**						
1	Diluted Hydrogen Sulphide		◆		◆		◆
2	Ammonium Nitrate (blasting agent)			●			
E	**Chemicals (industrial)**						
1	Soil conditioning foam		●		◆		
2	Polymers (all types)		●		◆		
F	**Suspension Fluids**						
1	Bentonite		●		◆		
2	Slurry admixtures (chemicals)		●		◆		
G	**Grouts (all applications)**						
1	Cements	●		●		●	
2	Bentonite	◆	◆	◆	◆	◆	◆
3	Resins	◆	◆	◆	◆	◆	◆
4	Sodium silicate	◆	●	◆	●	◆	●
5	Chemicals (admixtures)	●	●	●	●	●	●
6	Salts (accelerant)	◆	◆	◆	◆	◆	◆
H	**Petroleum Products (POLs)**						
1	Hydraulic oils	◆	◆	◆	◆	◆	◆
2	Greases	◆	◆	◆	◆	◆	◆
3	Lubricants	◆	◆	◆	◆	◆	◆
I	**Consumables and Wear Parts**						
1	Metallic	◆	◆	◆	◆	◆	◆
2	Plastics	◆	◆	◆	◆	◆	◆
3	Non-ferrous metals	◆	◆	◆	◆	◆	◆

Table 2: Tunnel Spoil Materials – Spectrum

● Frequent and common occurrence; dominant feature to be considered in the planning stage

◆ Seldom occurrence: need to carefully address in the geological reports and data

∇ Very rare occurrence: likely needs special equipment and safety systems to handle successfully

4.4.1 Boston Harbour – Deer Island Outfall Tunnel, Boston, Massachusetts, USA

The Deer Island Effluent Outfall Tunnel Project was a 12-year-long project begun in 1991. It was a critical element in a large composite plan to improve water quality in the Boston Harbour and to restore marine ecosystems and habitats that had been impacted from excessive pollution. Construction of the 14.5 km (9 mile) long single-heading outfall tunnel encountered many severe challenges that delayed the final completion of the project by several years. The following is a summary of the ground and groundwater conditions encountered along the tunnel alignment.

- **Geology**
  Tunnel strata was massive argillite with fractures
- **Groundwater**
  Seawater (salty) inflows
- **Recharge**
  Infinite from the overlying Boston Harbour
- **Initial lining**
  Ungasketed precast tunnel liner with backfill grouting
- **Final lining**
  None; pressurized sewage outfall tunnel, when in operation
- **Results**
  Complete overhaul to original tunnel water handling system:
  - Multiple groundwater pumping capacity upgrades
  • Added water collection system
  • Added water in-line pumping station
  - Multiple pump station replacements
  - Electrical power back-up systems to avoid severe tunnel flooding

Please see Figure 6 that illustrates the overall tunnel arrangements including single access shaft and sea floor diffusers installed for the Deer Island Effluent Outfall Tunnel.

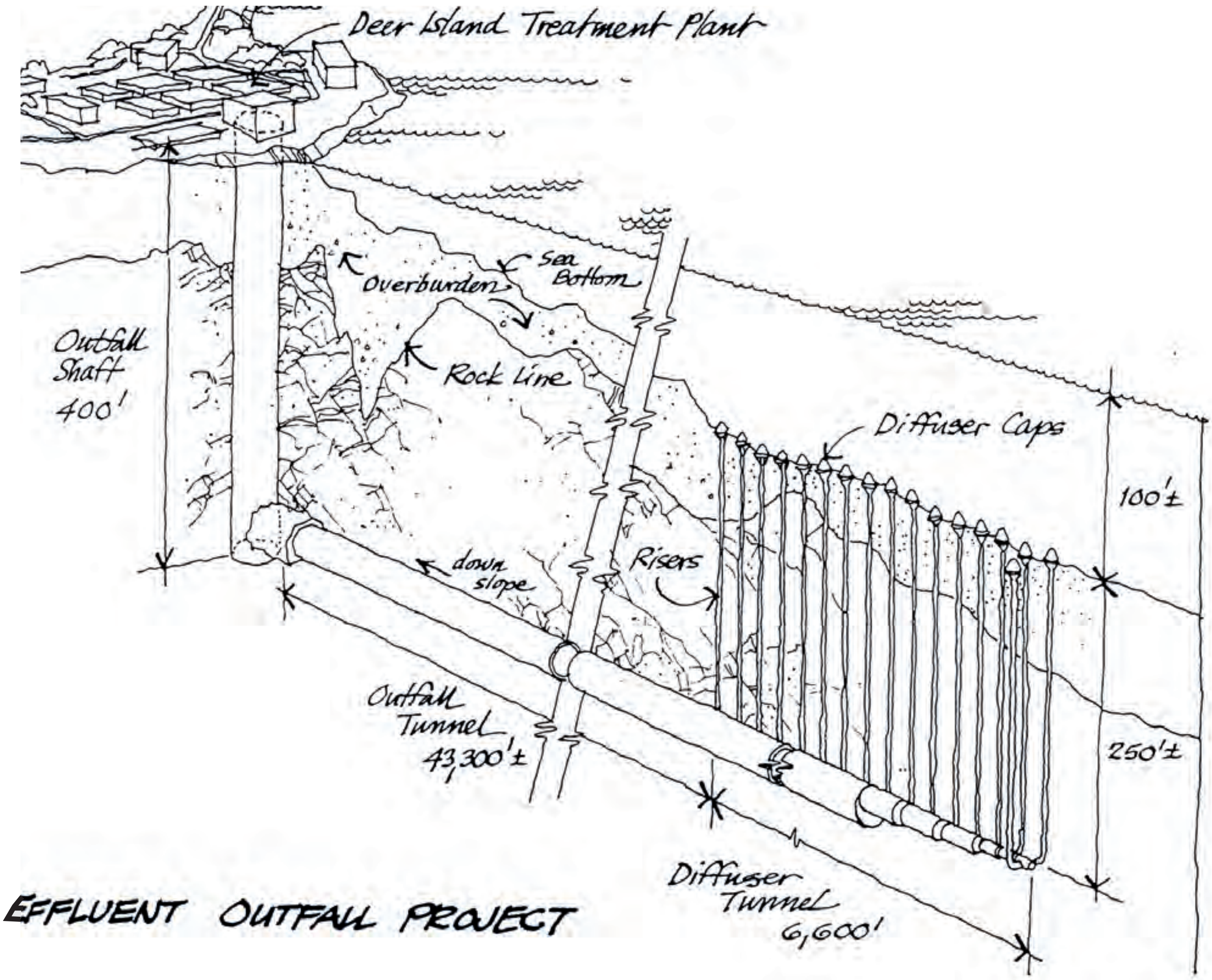


Figure 6: Deer Island Effluent Outfall Tunnel – Isometric View
Isometric view of the Deer Island Effluent Outfall Tunnel in Boston, Massachusetts. This tunnel was the largest and most challenging of all surface and underground facilities designed to improve water quality in the Boston Harbour area. Project duration was 12 years.

4.4.2 OARS Tunnel – Columbus, Ohio, United States

The Olentangy Augmentation Relief Sewer (OARS) Tunnel Project was a United States Environmental Protection Agency (US-EPA) Consent Decree initiated tunnel project begun in 2010 to contribute to the clean-up of the Scioto River in Columbus, Ohio, United States. The goal was to intercept existing outfalls discharging into the river, therefore, improving water quality and aquatic life by conveying untreated sewage to a nearby processing plant for enhanced treatment. The following is a summary of the ground and groundwater conditions encountered along the tunnel alignment.

- **Geology**
  Limestone with occasional cherts elements.
- **Groundwater**
  Residing in vuggy ground (Karst formation) with continuous open seams and solution cavities
- **Dewatering**
  Very flat groundwater drawdown curve and very large volumes and pumping rates needed to achieve any meaningful pressure and inflow relief
- **Recharge**
  Infinite from the in-situ strata
- **Results**
  Substantial overhaul to the TBM spoil handling system:
  - Installed slurry spoil handling system (water media) and equipment
  - Installed and surface solids separation plant
  - Install enhanced surface level water handling and treatment system

4.4.3 Arrowhead Tunnels Project – San Bernardino, California, United States

The Arrowhead Tunnels project was a strategic water conveyance project conceived in the late 1990's as a key element of the Inland Feeder Program near San Bernardino, California, United States. The project consisted of two RCCP tunnels totalling 6,840 m (22,443 LF) constructed for the Metropolitan Water District of Southern California (MWD) between 2002 and 2009. See Figures 7 and 8). The tunnels were designed to convey 28 m^3/sec (1,000 ft^3/sec) raw water to a local area reservoir for further treatment, distribution and use in Southern California. The following is a summary of the ground and groundwater conditions encountered along the tunnel alignments.

- **Geology**
  Highly altered granitic and gneissic formation
  - Frequent water bearing faults and shears
  - Brecciated zones with high groundwater pressures
- **Groundwater**
  High groundwater heads (pressures):
  - Waterman Tunnel: 185m (600 ft), 18.5 bar
  - Strawberry Tunnel: 275m (900 ft), 27.5 bar
- **Dewatering**
  Not possible from the surface
  - Only limited inflows allow into the tunnel
  - Extensive pre-excavation grouting needed for water and ground control
- **Recharge**
  Sensitive issues to address and remain in compliance:
  - Slow groundwater level recovery
  - Severe ecological impacts due to loss of overlying surface and near surface groundwater reserves due to depletion
- **Results**
  Substantial overhaul to the TBM spoil handling system:
  - Enhanced electrical power supplies (uninterruptable)
  - Added slurry spoil handling system and equipment
  - Added enhanced water handling and treatment system to meet water quality discharge criteria

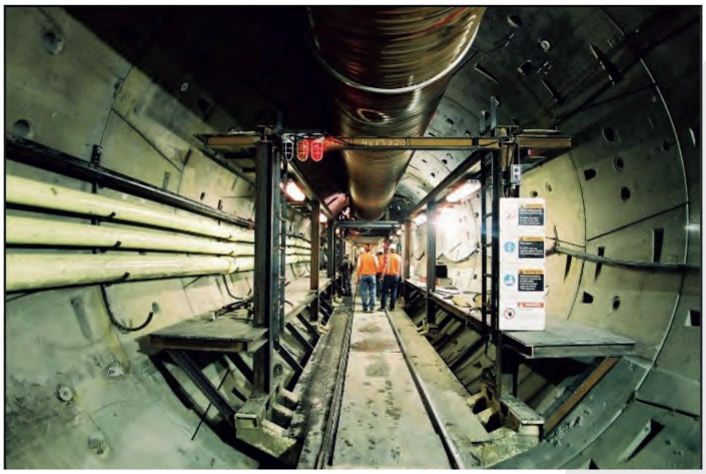


Figure 7: Arrowhead Tunnels Project – TBM
General arrangement of the TBM trailing gear, utility systems, tunnel spoil haulage (train) system.

Figure 8: Arrowhead Tunnels Project – Cross-Section
General arrangement of the tunnel cross-section showing utilities and spoil haulage (train) system.

The handling, treatment and disposal of all spoil materials from tunnelling operations from health and safety perspectives are well documented. It could not be overstated, the importance of building safety programs into the initial project concepts and designs. To this end, knowledge and full assessment for the health and safety exposures and risks and systems need to be firmly established from the «first scratch on paper» of the tunnel concepts. In the absence of this essential commitment, it is highly likely that the project will encounter unanticipated challenges and delays related to the successful handling, treatment and final disposal of all types of tunnel spoil materials. Moreover, the progress through critical stages and Hold Points, in the design program may be severely impacted without a full assessment of the risks resulting from products of tunnel excavation. Essential treatment and evaluation of disposal options including repurposing and remanufacturing into suitable end products must be assertively addressed.

The flow chart shown above in Figure 5 illustrates both incoming and outgoing materials from tunnelling operations; mechanized and conventional. Health and safety issuers are apparent for many when considering all aspects of handling, treatment and disposal options.
Several products of tunnel excavation are particularly notable from a health and safety perspective as summarized below and in Table 3. The following discussion describes some of the key attributes, safety hazards and explosive limits for methane and hydrogen sulphide as frequently encountered on tunnelling projects.

5.1 METHANE (CH_4) *Wikipedia* AND OTHER INFORMATION SOURCES COMBINED)

Methane is a chemical compound with the chemical formula CH_4 (one atom of carbon and four atoms of hydrogen). It is a Group-14 Hydride, the simplest alkane, and the main constituent of natural gas. The relative abundance of methane on earth makes it an economically attractive fuel, although capturing and storing it poses technical challenges due to its gaseous state under normal conditions for temperature and pressure.
At room temperature and standard pressure, methane is a colorless, odorless gas. The familiar smell of natural gas as used in homes is achieved by the addition of an odorant, usually blends containing tert-butylthiol, as a safety measure. As a gas, it is flammable over a range of concentrations (5.4 to 17%) in air at standard pressure.

Methane is non-toxic, yet it is extremely flammable and may form explosive mixtures with air. Methane is also an asphyxiantif the oxygen concentration is reduced to below about 16% by displacement, as most people can tolerate a reduction from 21% to 16% without ill effects. The concentration of methane at which asphyxiation risk becomes significant is much higher than the 5 to 15% concentration in a flammable or explosive mixture. Methane off-gas can penetrate the interiors of buildings near landfills and expose occupants to significant levels of methane. Some buildings have specially engineered recovery systems below their basements to actively capture this gas and vent it away from the building.

5.2 HYDROGEN SULPHIDE (H_2S) (WIKIPEDIA AND OTHER INFORMATION SOURCES COMBINED)

Hydrogen sulphide is a chemical compound with the formula H_2S. It is a colorless chalcogen hydride gas with the characteristic foul odor of rotten eggs. It is poisonous, corrosive, and flammable. Hydrogen sulphide is often produced from the microbial break-down of organic matter in the absence of oxygen, such as in swamps and sewers; this process is commonly known as anaerobic digestion which is done by sulphate-reducing microorganisms. H_2S also occurs in volcanic gases, natural gas, and in some sources of well water.

Hydrogen sulphide is slightly denser than air. A mixture of H_2S and air can be explosive. Hydrogen sulphide burns in oxygen with a blue flame to form sulphur dioxide (SO_2) and water. Hydrogen sulphide is a highly toxic and flammable gas (flammable range: 4.3 to 46%). Being heavier than air, it tends to accumulate at the bottom of poorly ventilated spaces. Although very pungent at first (it smells like rotten eggs), it quickly deadens the sense of smell, creating a temporary incident of anosmia so victims may be unaware of its presence until it is too late. For safe handling procedures, a hydrogen sulphide Safety Data Sheet (SDS) should be consulted.

Hydrogen sulphide is a broad-spectrum poison, meaning that it can poison several different systems in the body, although the nervous system is most affected. The toxicity of H_2S is comparable with that of carbon monoxide. Please see Figure 9 that graphically illustrates the escalating hazard associated with increasing H_2S concentrations.

Exposure Limits stipulated by the United States government

- **10 ppm REL-Ceiling (NIOSH)**
  - Recommended Permissible Exposure Level (REL) ceiling; the recommended level that must not be exceeded, except once for 10 minutes in an 8-hour shift, if no other measurable exposure occurs.
- **20 ppm PEL-Ceiling (OSHA)**
  - Permissible Exposure Level (PEL) ceiling; the level that must not be exceeded, except once for 10 minutes in an 8-hour shift, if no other measurable exposure occurs.
- **50 ppm PEL-Peak (OSHA)**
  - Peak Permissible Exposure Level (PEL); the level that must never be exceeded).
- **100 ppm IDLH (NIOSH)**
  - Immediately Dangerous to Life and Health (IDLH); the level that interferes with the ability to escape.

NIOSH National Institute for Occupational Safety and Health (United States)

OSHA Occupational Safety and health Administration (United States)

Concentrations and Effects

- 0.00047 ppm (or 0.47 ppb) Odour threshold, the point at which 50% of a human panel can detect the presence of an odour without being able to identify it
- 10 to 20 ppm
  Borderline concentration for eye irritation
- 50 to 100 ppm

Leads to eye damage

- 100 to 150 ppm
  Olfactory nerve is paralyzed after a few inhalations, and the sense of smell disappears, often together with awareness of danger
- 320 to 530 ppm
  Leads to pulmonary edema with the possibility of death
- 530 to 1,000 ppm
  Causes strong stimulation of the central nervous system and rapid breathing, leading to loss of breathing
- 800 ppm
  Lethal concentration for 50% of humans for 5 minutes' exposure (LC50)
- Over 1,000 ppm
  Cause immediate collapse with loss of breathing, even after inhalation of a single breath.

Table 3 below summarizes the primary attributes, properties and hazards to tunnelling operations (including spoiling handling and storage) using both mechanical and conventional excavation approaches.

Lower Explosive Limit (LEL)

The term "LEL" is used extensively and is short for "Lower Explosive Limit" is defined as the lowest concentration (by percentage) of a gas or vapor in air that is capable of producing a flash of fire in presence of an ignition source (arc, flame, heat, etc.). Gas concentrations lower than the Lower Explosive Limit are "too lean to burn".

The maximum concentration of a gas or vapor that will burn in air is defined as the "Upper Explosive Limit" (UEL). Above this level, the mixture is "too rich to burn". The range between the LEL and UEL is known as the flammable range for that gas or vapor. Please refer to Figure 10 for a graphic representation of the various gas concentrations, flammability and explosive characteristics.

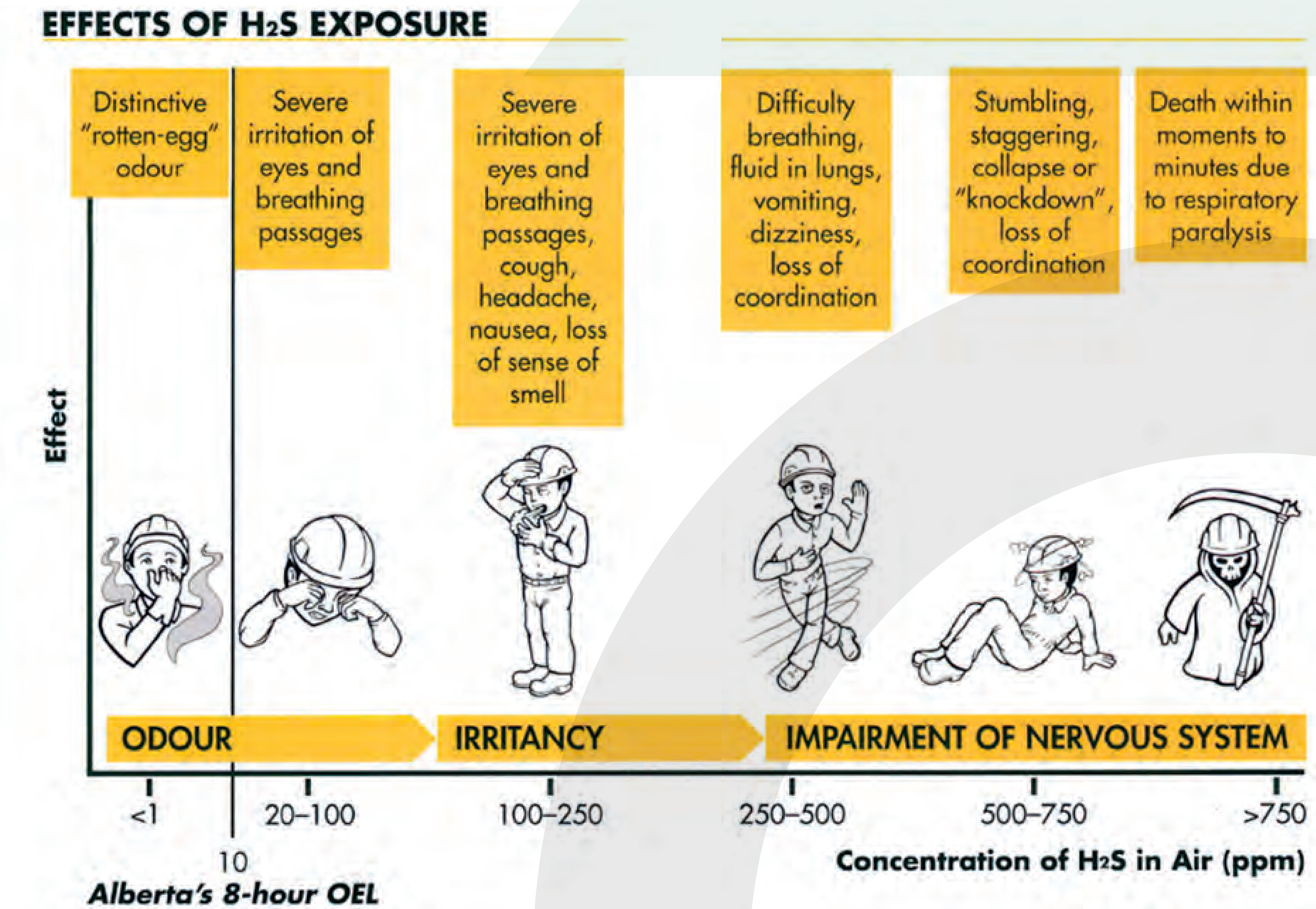


Figure 9: Hydrogen Sulphide – Exposure Limits and Hazards
Graphic representation of the exposure limits and durations (PEL) and human reactions from hydrogen sulphide gas. (Courtesy of the Province of Alberta, Canada)

ITEM	ATTRIBUTE OR PROPERTY	GAS FROM SUBSURFACE STRATA		SAFETY CODE REFERENCES		
		METHANE (CH_4)	HYDROGEN SULPHIDE (H_2S)	USA OSHA	CAL OSHA	UK HSE
A	**HAZARDS**					
1	Flammable Flash point temperatures Auto ignition temperatures	• -188°C (–306°F) 537°C (999°F)	• - 82°C (–116°F) 232°C (450°F)	• • •	• • •	• • •
2	Combustible	•	•	•	•	•
3	Explosive ***Explosive – range***	• 5.4 to 17%	• 4.3 to 46%	• •	• •	• •
4	Corrosive	-	•	•	•	•
5	Toxic	-	•	•	•	•
6	Poisonous	-	•	•	•	•
7	Asphyxiantif (e.g. displaces O_2)	•	•	•	•	•
B	**PHYSICAL PROPERTIES**					
1	Density Density value Specific Gravity	***Lighter than air*** 0.716 g/l 0.544	***Heavier than air*** 1.539 g/l 1.19			
2	Colour	Colourless	Colourless			
3	Odour ***Odour comments***	Odourless Odorant added by gas suppliers	Rotten eggs Odour diminishes with exposure levels			
4	Human reactions		Incidents of anosmia (loss of smell with increasing H_2S exposure levels and durations)			

Table 3: Methane and Hydrogen Sulphide – Attributes and Properties
Summary of the primary attributes and properties associated with methene (CH_4) and hydrogen sulphide (H_2S) encountered in tunnelling operation including spoil material handling, treatment and final disposal stages.

OSHA Occupational Safety and Health Administration – United States
CAL California Occupational Safety and Health Administration – United States
HSE Health and Safety Executive – United Kingdom

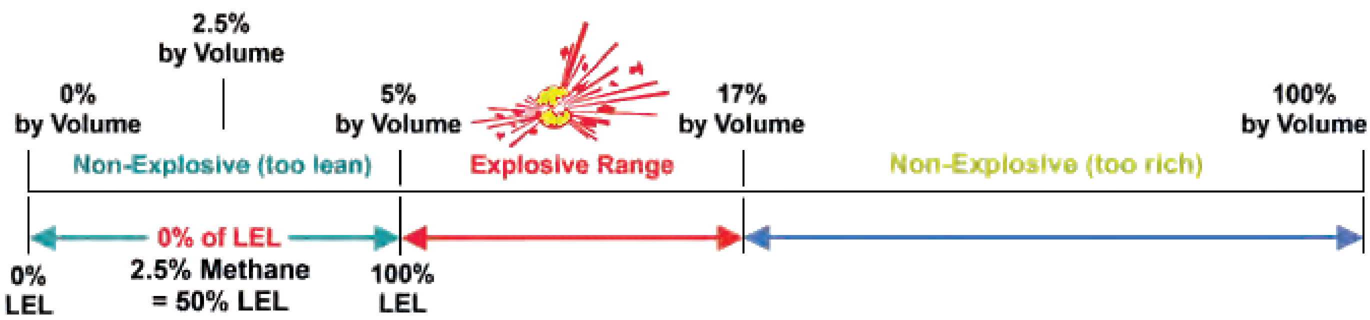


Figure 10: Methane – Lower and Upper Explosion Limits
Methane Lower Explosive Limit (LEL) = 5% by volume in air. Upper Explosive Limit (UEL) = 17% by volume in air. (Wikipedia)

5.3 Tunnel Dust Conditions, Confinement, Collection and Disposal

In the case where excessive dust quantities were encountered as a product of the tunnel excavation method, specialized collection and processing equipment is needed to be compliant with published Health and Safety regulations. Additional equipment and a modified ventilation system may include the following for example,

- Increased volumes of ventilation air
- Changes to ventilation air circulation and system configuration
- Installation of wet or dry scrubbers
- Enhanced air quality monitoring, testing and sample analysis
- Enhanced personnel training and protective equipment

Figure 11 below illustrates a modern dry dust scrubber and tunnel fan arrangement that could be deployed on both mechanized and conventional tunnelling operations.

The following is an abbreviated summary of the current California Occupational Safety and Health Administration (CalOSHA) regulations covering dust in tunnel and underground construction, published under their Tunnel Safety Orders (TSOs).

CalOSHA Subchapter 20 - Tunnel Safety Orders
Article 4 – Dusts, Fumes, Mist, Vapours and Gases

Article 1523.3 – Occupational Exposures and Respirable Crystalline Silica.

(a) *Scope and application. This section applies to all occupational exposures to respirable crystalline silica in construction work, except where employee exposure will remain below 25 micrograms per cubic meter of air (25 μg/m^3) as an 8-hour Time-Weighted Average (TWA) under any foreseeable conditions.*

(b) *Definitions. For the purposes of this section the following definitions apply:*

- *Action Level means a concentration of airborne respirable crystalline silica of 25 μg/m^3, calculated as an 8-hour TWA.*
- *Chief means the Chief of the Division of Occupational Safety and Health, or designee.*
- *Director means the Director of the National Institute for Occupational Safety and Health (NIOSH), U.S. Department of Health and Human Services, or designee.*
- *Competent Person means an individual who is capable of identifying existing and foreseeable respirable crystalline silica hazards in the workplace and who has authorization to take prompt corrective measures to eliminate or minimize them. The competent person must have the knowledge and ability necessary to fulfill the responsibilities set forth in subsection (g).*
- *Employee Exposure means the exposure to airborne respirable crystalline silica that would occur if the employee were not using a respirator.*
- *High-Efficiency Particulate Air (HEPA) Filter means a filter that is at least 99.97% efficient in removing mono-dispersed particles of 0.3 micrometers in diameter.*
- *Objective Data means information, such as air monitoring data from industry-wide surveys or calculations based on the composition of a substance, demonstrating employee exposure to respirable crystalline silica associated with a particular product or material or a specific process, task, or activity. The data must reflect workplace conditions closely resembling or with a higher exposure potential than the processes, types of material, control methods, work practices, and environmental conditions in the employer's current operations.*
- *Physician or Other Licensed Health Care Professional (PLHCP) means an individual whose legally permitted scope of practice (i.e., license, registration, or certification) allows him or her to independently provide or be delegated the responsibility to provide some or all of the particular health care services required by subsection (h).*
- *Respirable Crystalline Silica means quartz, cristobalite, and/or tridymite contained in airborne particles that are determined to be respirable by a sampling device designed to meet the characteristics for respirable-particle-size-selective samplers specified in the International Organization for Standardization (ISO) 7708:1995: Air Quality – Particle Size Fraction Definitions for Health-Related Sampling.*

Figure 11: Dry Dust Scrubber and Tunnel Fan Assembly
Skid-mounted tunnel fan and in-line dry dust scrubber used for both mechanized and conventional tunnelling operations. (Courtesy of CFT and Korfmann)

- *Specialist means an American Board Certified Specialist in Pulmonary Disease or an American Board Certified Specialist in Occupational Medicine.*
- *This Section means this respirable crystalline silica standard, Section 1532.3.*

(c) Specified exposure control methods. (1) For each employee engaged in a task identified on Table 1, the employer shall fully and properly implement the engineering controls, work practices, and respiratory protection specified for the task on Table 1, unless the employer assesses and limits the exposure of the employee to respirable crystalline silica in accordance with subsection (d).

California Code of Regulations, Title 8, Section 1532.3. Occupational Exposures to Respirable Crystalline Silica.

CalOSHA Subchapter 20 - Tunnel Safety Orders
Article 12 – Ventilation and Dust Control
Article 8438 – Dust Control

(a) Water or other effective means shall be used to control dust where drilling, grinding, or other dust producing operations occur in accordance with Section 1538(a) of the Construction Safety Orders.

(b) Sprinklers or other effective means shall be provided to control dust produced at dumps, conveyors, chutes, and other transfer points.

c) Whenever water sprinklers are used to control dust at loading points, they shall be capable of being operated by the person(s) responsible for conducting the loading.

(d) The muck pile shall be wet down prior to mucking and kept wet during the mucking operations in order to control dust.

(e) If compliance with the requirements of this and other tunnel safety orders fail to hold dust concentrations in all parts of the tunnel within limits specified in Section 5155 of the General Industry Safety Orders, additional steps called for in Article 107 of those orders shall be followed.

5.4 TUNNEL DUST CONTAINMENT AND DISPOSAL – TUNNEL PROJECT EXAMPLE

The following are selected excerpts from a soon to be published paper at WTC 2022 in Copenhagen related to tunnel construction dust conditions and the successful application of engineering (and specialized equipment) controls that largely eliminated the hazards and allowed tunnel excavation to proceed safely. The paper, titled. "Tunnel Dust Control Project" by Tim Warden (listed in Section 14 – References and Additional Reading Materials) relates to an undisclosed tunnel project in British Columbia, Canada.

This case study describes the implementation of a new Wet Type Dust Extraction System to control fugitive dust generated at a large tunnel project in British Columbia, Canada. The tunnelling project was designed to included two tunnels, approximately 12.5m (41 feet)

and 4.0m (13 feet) diameter, each 1,000 m (3,050 feet) long. Both tunnels were faced with severe dust and ventilation challenges during the initial phase of the project. Regulators had tested the air and found the dust levels to be unacceptable and required mitigation devices to be implemented before the project could commence.

The paper briefly describes the operation and expedient implementation of an exhaust ventilation and dust control system that would remove particulates at a high efficiency acceptable for emissions while providing proper ventilation and dust levels within the tunnel construction area. Although environmental operating conditions were a huge driving force for the control device, other operational advantages were quickly noticed that further drove this system to be fully implemented on a permanent basis.

The discussion will include the implementation of an exhaust ventilation and dust control device and the test data that illustrates the 'before' and 'after' results of dust levels at critical locations throughout the tunnel construction area.

Dust was a Significant Safety and Health Issue for the Project

According to the regulatory *authority, WorkSafeBC, the following requirements had to be met for underground mining or tunnelling projects:*

22.81 Dust Control

(1) Mechanical excavating devices, such as tunnel boring machines and road headers, must have an effective dust control and ventilation system which maintains workers' exposure to dust below the applicable exposure limits in this Regulation.

(2) Such systems must be maintained in good working order and must be operational whenever the mechanical excavating device is working.

When dealing with dust that contains silica, there are specific silica limits outlined by WorkSafeBC with control methods suggestions:

2.1.1.2 Engineering Controls

Making physical modifications to facilities, equipment, and processes can reduce exposure. Some questions to consider:

- *Can local exhaust ventilation be used on all equipment that generates silica dust?*
- *Can water be used to prevent dust from becoming airborne ?*
- *Can the areas that generate large amounts of dust be enclosed, and have proper ventilation to clean the air?*

Regulatory compliance details for the various types of silica in this case study the limits for Amorphous Silica exceeded the 1.5 mg/m3 limit in the worker area. In addition to concerns over silica dust exposure, WorkSafeBC also notes total dust limits as described below:

The Board categorizes particulates that are insoluble or poorly soluble in water and do not cause toxic effects other than by inflammation or the mechanism of «lung overload», as «nuisance dusts».

A «nuisance dust» will have an exposure limit or TLV of 10 mg/m3 for total particulate. It is recognized that the respirable fraction of «nuisance dusts» may also be measured. The equivalent exposure limit for respirable particulate is 3 mg/m^3. Respirable particulate refers to the fraction of inhaled dust that is capable of passing through the upper respiratory tract to the gas exchange region of the lung. Total particulate refers to a wide range of particle sizes capable of being deposited in the various regions of the respiratory tract.

https://www.worksafebc.com/en/law-policy/occupational-health-safety/searchable-ohs-regulation/ohs-policies/policies-part-05

De-Duster System Design Parameters and Equipment Selection

There are basically two main criteria for the selection of the proper De-Duster for an exhaust ventilation system.

- *Air Volume*
- *Static Pressure*

The entire selection process boils-down to those two main parameters. There are extensive calculations for determining the air volume requirements which are for this discussion based on the tunnel dimensional parameters. The length of the tunnel is then used along with the desired duct carrying velocity for the specific type of dust particles to in turn provide the criteria to calculate the duct friction loss factors for total static pressure that the fan must overcome. A typical tunnel application is shown below in Figure 12.

Air Flow Requirement Calculations and De-Duster Principles of Operation

The first step in determining the air flow requirements is to total up the amount of air needed for each piece of diesel equipment, and the recommended amount of air so to provide clean air at the face. The diesel equipment is determined by the size of each piece and empirical standards on how much air flow is needed to clear away the exhaust fumes from each piece. The dust level control requirements are based on the cross-sectional area of the face and the velocity needed across the face in order to move the dust in a controlled manner. The larger of the two numbers is used for design purposes.

Second, once the total air-flow requirements are determined and then it is necessary to calculate the static pressure of the system. This is done using standard principles from the Industrial Ventilation Handbook. The handbook combines the actual duct length with equivalent duct length factors such as exit losses and coupling losses. This will provide an effective duct length.

Using Industrial Ventilation Handbook principles the static pressure is then calculated based on the "effective duct length", total air-flow requirements, duct diameter, and the calculated air velocity inside of the ductwork. Other losses in turn add to the total losses, such as the entrance losses on the duct inlet, elbows, and a velocity loss due to the air velocity in the ductwork. The anticipated break-down of these friction losses and the total design loss will be used in the De-Duster equipment selection.

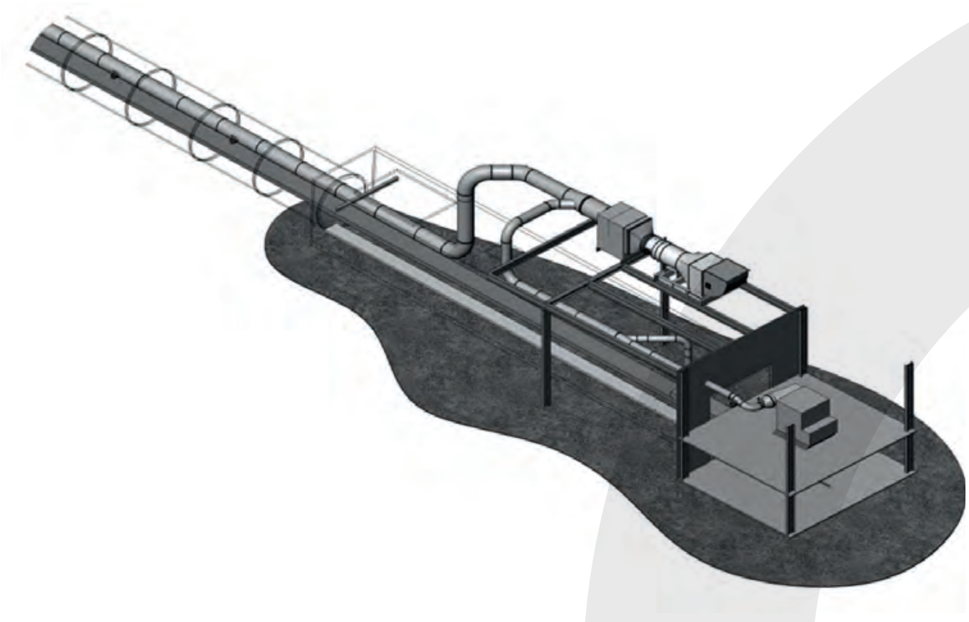


Figure 12: Tunnel Ventilation Plant with De-Duster – Portal Area Installation
Rendering of a plant and equipment arrangement including a De-Dusting unit at a tunnel portal where the ventilation system is operated in exhaust mode. (Courtesy Englo, Inc.)

The inlet ducting brings in the fouled air from the tunnel into the De-Duster inlet. See Figure 13 below. The front portion of the machine mixes the water and the dust together in a very rapid exchange of pressure and the dynamic action of the integrated impeller, as shown in Figure 14 below.

After the rapid mixing of dust with the water, the dust laden water travels around the motor in a sealed compartment so to keep the motor in the clean air as illustrated in Figure 15. After leaving this bifurcated section it is again sprayed with water using an internal water spray system as shown in Figure 16 in order to further saturate the dust particles and to provide better air cleaning the next step is to separate the dust laden water from the air stream. This is accomplished in the rear rectangular section of the machine using a unique series of mist eliminators and impingement panels.

Figure 13: De-Duster – Fixed Mounted Demo Unit
General arrangement of a De-Duster unit; linked to the tunnel ventilation system. (Courtesy Englo, Inc.)

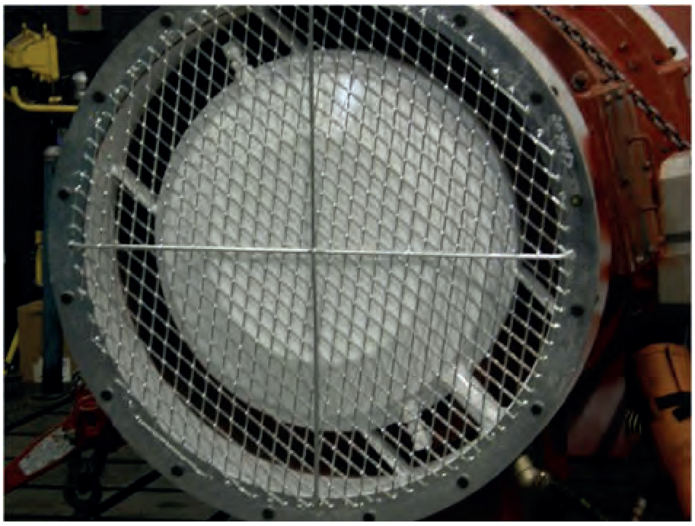


Figure 14: De-Duster – Integrated Impeller
Inlet cone and impeller of a De-Duster unit linked to a tunnel ventilation system. (Courtesy Englo, Inc.)

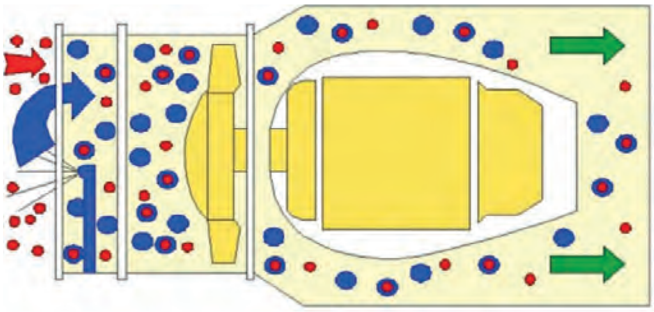


Figure 15: De-Duster – Dust Capture Principles
Schematic of air and water flows convergence in the De-Duster ventilation uit. (Courtesy Englo, Inc.)

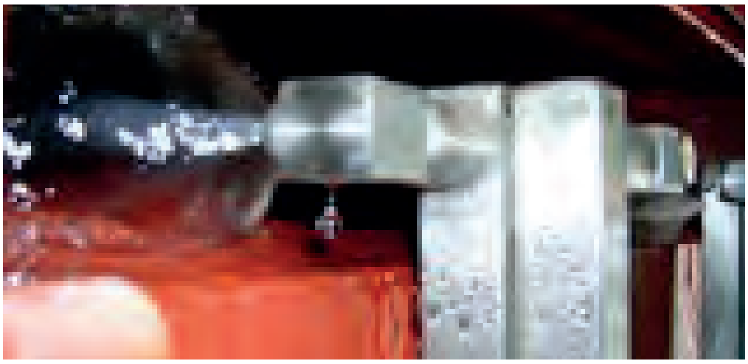


Figure 16: De-Duster – Internal Water Spray
Internal water spray (atomizing) nozzle in the De-Duster unit. (Courtesy Englo, Inc.)

6 >> Local and National Regulations for Tunnel Spoil Disposal

Clearly this section is a point that we need help to further develop as more information is obtained from global sources. Hence this is considered a "living document" and constantly subject to change and further expansion. Many of the pertinent points, in the authors' opinion include the following:

- What contaminants are being tested
- How often are they tested; e.g. per shift, per day.
- Not part of the remit of this report, but there is no information that we can find that states that if a soil is irredeemably contaminated, why is it acceptable to dispose of it in an approved dumping area; i.e. what makes that disposal area acceptable for say, asbestos, molybdenum for example and not another.
- Why has a whole project in Australia been stopped because they cannot dispose of the soil in an approved dump. The entire area is contaminated anyway.
- From what the report writers and researchers have been able to see, in most countries, there are no unified regulations relating to soil disposal. In the USA for example, there are different regulations in counties within states, therefore, potentially hundreds of differing regulations within one country.

6.1 GLOBAL WASTE HIERARCHY

Once it has been established that the tunnel excavation spoil contains none of the above, it then becomes a matter of how to dispose of the material according to the waste hierarchy. Please see Figure 17.

The following national summaries describe only a very small portion of the specific regulations and practices affecting tunnel spoil management including treatment and final disposal options. Please also refer to the Section 14 – References and Additional Reading Materials. This is not an exhaustive or definitive summary and as described in the conclusions to the DRAGON Project (Sections 11 and 15), even the European Union has many national regulations (and preferences) for excavation spoil testing, treatment and disposal options with additional restrictions, based location and social goals.

It is also acknowledged that all regulations are frequently changed with variable levels of enforcement, mitigations and "off-sets" (see Arrowhead Tunnel Case Study for example). For most projects, official permits and approvals from regulatory agencies are required for handling, treatment and final disposal of all products of excavation. These would include rock, soil, water, gas, dust, POLs and most contaminants (i.e. hazardous materials) as listed in Table 2.

6.2 NATIONAL SUMMARIES AND GUIDELINES

The following provides very brief summaries, process flow charts and national references for the handling, treatment and disposal requirements of tunnel spoil materials from a very small sampling of countries having well established procedures in place. It does not presently include all countries where tunnelling operations are underway.

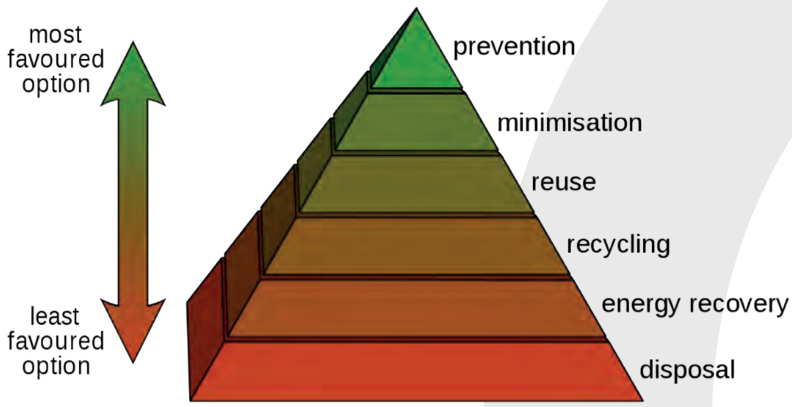


Figure 17: The Waster Hierarchy. Popular image of waste management with comparison of "most favoured" (prevention) to "least favoured" (disposal) options; aptly colour coded for simplicity.

Nonetheless, this sample is useful in describing some of the complexities involved with tunnel spoil as well as many of the highly regulated procedures to be addressed, particularly during the tunnel design and development stage. Additional revisions to this paper will further build-out national references for tunnel spoil handling, treatment and disposal regulations together with supporting examples and Case Studies. Countries listed below are in alphabetical order for convenience.

Australia

Please be aware that the authors are writing this section as an opinion on the current norms in Australia. Our apologies where there maybe errors and be assured that any such errors will be amended in subsequent revisions.

Australia is similar to Italy in its approach to ensuring the EPB tunnelling operation has zero adverse effects to its environment. There are differences in approach/limits between the States and New Zealand, but the most recent example is detailed below.

The Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) wrote a document in 2000 called "Australian and New Zealand Guidelines for Fresh and Marine Water Quality". It is a comprehensive document detailing limits for pollutants in fresh and marine water. On page 3.4-5 of Volume 1, Table 3.4.1, there is a list of chemicals and their limits expressed in µg/l for 80, 90, 95 and 99% Trigger Values for toxicants at alternative levels of protection. There is a further section, (linked to the document table), to a comprehensive guideline on how to choose which limit for each aquatic eco-system.

Three surfactants are listed, namely;

- Linear alkylbenzene sulfonates (LAS)
- Alcohol ethoxyolated sulfate (AES)
- Alcohol ethoxylated surfactants (AE)

6 >> Local and National Regulations for Tunnel Spoil Disposal

Further information on these chemicals can be found in Section 8.3.7.21 on page 291 of Volume 2 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* Please refer to Section 14 – References and Additional Reading Materials.

At this point, the Client has requested the tunnelling Contractor test the foams available on the market to see which has the least environmental impact, and which has none of the above chemicals within. This work was carried-out by an independent environmental assessment company that, in much the same way as Italy, tested for biodegradability and ecotoxicity in water and soil.

With the above information in hand, an informed decision could be made on the most environmentally sound product to use. The next stage would be to conduct laboratory trials to see if ground conditioning could be properly practically used.

Canada

One of the biggest issues in Canadian tunnelling, and a legacy from historical mining operations is understanding and attempting to quantify the nature of Acidic Rock Drainage (ARD) and Metal Leaching (ML) within the spoil from a tunnel. Acid rock drainage occurs naturally within some environments as part of the rock weathering process and is exacerbated by large-scale earth disturbances characteristic of tunnelling construction activities. After being exposed to air and water, oxidation of metal sulphides (often pyrite, which is an iron-sulphide, or similar iron (Fe) bearing minerals) within the surrounding rock and overburden begins to generate acidic leachate. Within Canada, the Provincial Government of British Columbia took the lead in developing a policy and guidelines for metal leaching and acid rock drainage (ML/ARD) at mine sites in 1998 (BC MEM & MOE, 1998 and, Price & Errington, 1998). The policy sets out three key steps that should be undertaken to predict ML/ARD as part of a documented prediction program for tunnelling, as follows:

- Identify and describe all geological materials excavated, specifically the mineralogical assemblage, exposed or otherwise disturbed by tunnelling.
- Predict the ML/ARD potential and (where applicable) the timing for each geological material in the forms (i.e. particle size) and environmental conditions in which it will be exposed.
- Develop a mitigation and monitoring program based on the predicted ML/ARD potential and environmental protection needs.

It should be implicit that in terms of the lifecycle of a tunnelling project the various stages of investigation and geotechnical data reports should describe and predict if ML/ARD is an issue on a given tunnelling project. Initial simplistic testing of rock samples is required to assess if ML/ARD might be an issue on a given project following geological characterization through static tests; Trace element content, acid-base accounting and mineralogy examination. However, to follow up on this testing and to assess the timing of acid and metal generation following exposure to the air and water, kinetic testing is required (typically undertaken in humidity cells). The Humidity Cell Tests (HCT) mimic the excavations environment, to analyse the equilibrium of acid generation in leachate water quality over time. Results of the HCT may take months to years to achieve and often require in-depth consultation between the project’s owner, consultant and other stakeholders prior to discontinuation.

In the preparation of contract documents for a tunnelling project, and assuming a traditional design-bid-build contract the presence and extent of ML/ARD rock should be indicated within the Geotechnical Baseline Report. Specifications should be prepared for the suitable transport, storage and permanent disposal of ML/ARD rock. In this regard, subaqueous deposition is often favoured as it tends to arrest the micro-bacterial weathering process that forms acid and metals leachate. Subaqueous environments can include foreshore rehabilitation, Disposal-at-Sea (DaS) and within a flooded tunnel. Where subaqueous deposition cannot be carried out, typically a geomembrane lined, and encapsulated cell is used to ensure the hydro-geological containment of the rock and prevent water infiltrating through it in the presence of oxygen. More recent projects have shown that permitting for subaqueous deposition outside of the tunnel environment can be time consuming and rigorous, often requiring details that may not be known until construction commences. That being said, it is an option worth exploring when and as applicable. On any tunnelling project it is important that the project Owner is made aware of the risks of ML/ARD and that long-term monitoring of any disposal site or stockpile may be warranted.

Another issue effecting Canadian tunnels, particularly those excavated under or adjacent to saline water bodies, is the disposal of saline muck or spoil. As there is no specific definition of saline tunnel spoil and its associated parameters, the applicable regulation that is often deferred to in Canada is the Canadian Drinking Water standards. Soil is considered to be salty or saline if either (or both) the chloride and sodium ion concentration exceed 100 µg/g (chloride ion concentration for drinking water standards) and/or 1,000 µg/g (sodium ion concentration for soil invertebrates and plant standard). Investigating, characterizing and quantifying the potential for saline muck or tunnel spoil should be carried out in any excavation close to the marine environment or foreshore of saline water bodies. The assessment should consider the appropriate management and disposal of saline spoil during tunnelling, with a clear statement in the Geotechnical Baseline Report on this issue and the estimated quantification thereof. The discharge environment of the saline water associated with slurries and tunnel muck must also be investigated to ensure provincial regulatory requirements will be met to satisfy permitting.

Germany

The drilling mud from mechanized tunnelling is disposed of in different ways depending on the type of advance. In the EPB tunnelling method, the excavated soil acts as the supporting medium in conjunction with various conditioning agents and water. This soil mixture is disposed of after the first use without being reused during the advance.

The bentonite suspension in hydroshield tunnelling, on the other hand, is separated into a solid and liquid fraction after a multi-stage filtration process in a separation plant specially designed for this purpose. The suspension obtained from the separation process is transported to the excavation chamber again when it is of sufficient quality in combination with freshly produced suspension and is used again for tunnelling as a supporting and conveying medium. This cycle is repeated as long as the bentonite suspension retains its supporting and conveying capacity. If the used suspension no longer meets the requirements for support pressure transmission and pumping capacity, it is finally removed from the circuit and disposed of. When disposing of drilling mud, it must be verified if the degraded soil material it contains is contaminated.

In Germany, the Waste Framework Directive of the European Parliament is transposed into national law by the Act on the Promotion of the Closed Substance Cycle Economy and Ensuring Environmentally Sound Management of Waste in Accordance with European Directives (AVV). Together with the Federal Soil Protection Act (BBodSchG) and the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV) contained therein, the Closed Substance Cycle Waste Management Act (KrWG) represents the central regulations for the area of soil protection in sectoral environmental law.

In addition, there are numerous environmental laws that contain soil protection regulations. Such regulations can be found in particular in waste law, but also in water and nature conservation law. In addition to the Closed Substance Cycle and Waste Management Act (KrWG), there are state waste laws and municipal statutes that further implement the requirements of the federal law. The lack of a uniform federal regulation leads to disparate and complex situations in the planning and construction phases of tunnel construction projects. Currently, uniform national regulations are to be set-up with the intention of creating legal certainty for the parties (producers, processors, disposers) involved in the waste cycle.
The introduction of the Substitute Building Materials Ordinance is intended to establish for the first time nationwide and legally binding requirements for the production and installation of mineral substitute building materials. The aim is to promote the circular economy in the area of mineral waste and to improve the acceptance of secondary and substitute building materials by harmonizing and concretizing the legislation (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), June 2021).

In Germany, the following regulations are valid for the disposal of the excavated soils in tunnelling (in addition to further federal and local regulations and laws):

- EWC European Waste Catalogue
- AVV German Waste Catalogue
- KrWG Circular Economy Act – the main German Management Waste Act
- BBodSchG Federal Soil Protection Act
- BBodSchV Federal Soil Protection and Contaminated Sites Ordinance
- DepV Landfill Ordinance
- WHG Water Resources Act
- LAGA German Working Group of Federal States on Waste
- LAWA German Working Group of Federal States on Water
- LABO German Working Group of Federal States on Soil Protection

Italy

In Italy, there has been perhaps more attention given to this topic than anywhere else in the world. There was an instance in Florence where the management of a tunnel project were arrested for allegedly contaminating the spoil to save money in appropriate disposal. This is the catalyst for the recent legislation. In Section 8 – Case Studies and Project Examples, the example of the Santa Lucia Tunnel is given in somewhat greater detail. In essence, in this Project, any soil that has been excavated from the tunnel, is not allowed to leave the jobsite until it has been shown to be as no more danger to the environment than before it was mined. If only the lixiviation test is considered, the only parameter influenced seriously by the foam is the Organic Content (COT). So, with the lixiviation test, the effect brought by surfactants to the soil is not really evaluated. For this reason, in Italy it is necessary to combine the lixiviation tests with some eco-toxicity tests, which measure the toxic effect towards several watery and terrestrial organisms. The spoil is permitted to leave the job-site area to its final disposal when;

- All the parameters measured with the lixiviation test are below the limits
- The eco-toxicity of the conditioned soil is the same of the natural soil (sometimes they accept a margin of 10 to 15%): this means that the addition of the conditioning agents do not modify, or modify only slightly, the toxicity of the natural soil.
- If the eco-toxicity of the conditioned soil is higher than the natural soil, then it is necessary to wait for the foam degradation, until the limit is respected.

New Zealand

On a new project in Auckland, the Client has asked for the soil to have a moisture content lower than 22% prior to being taken to the disposal site. This is specifically due to the dumping ground insisting that soil above this moisture content level could not be compacted properly. This is hugely problematic for the contractor when considering the in-situ moisture content is higher than this prior to ground conditioning.

The Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) wrote a document in 2000 called "Australian and New Zealand Guidelines for Fresh and Marine Water Quality". It is a comprehensive document detailing limits for pollutants in fresh and marine water. Further information on these chemicals can be found in Section 8.3.7.21 on page 291 of Volume 2 Please refer to Section 14 – References and Additional Reading Materials.

United Kingdom

It is a massively big undertaking to understand all the relevant documentation surrounding the existing documentation. Rather surprisingly and disappointingly, of all the myriad of industries covered, tunnelling does not appear to get a mention. The "rules and regulations" within though are comprehensive and to summarise them you need to follow seven steps:

- Does the waste need to be classified? In the case of tunnels always, yes.
- All tunnelling waste needs to be given a 6-figure code. Typically coming from Chapter 17-5 (Soil (including excavated soil from contaminated sites), stones and dredging spoil) of the above referenced documentation.
  - 17 05 03* soil and stones containing dangerous substances
  - 17 05 04 soil and stones other than those mentioned in 17 05 03

The above codes (*) are termed mirror codes, which mean that either the soil is or is not hazardous. A mirror code means further analyses need to be carried out to give an exact code.

Hazardous or not.

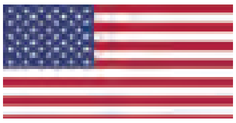
- An assessment of the chemicals within the soil needs to be undertaken. By sampling and analysing the waste to determine its composition –you must read Appendix D before undertaking any sampling, to ensure that sampling is appropriate, representative and reliable.
- Identify if the substances in the waste are "hazardous substances" or "Persistent Organic Pollutants".
- Assess the hazardous properties of the waste.
- Assign the correct code.

As can be seen from above, in a tunnel this is a massive undertaking, especially in areas where the historical land usage is sketchy. A list of 14 groups is listed below for reference.

- Explosive
- Oxidizing
- Flammable
- Irritant
- Acute toxicity
- Carcinogenic
- Corrosive
- Infectious
- Toxic for reproduction
- Mutagenic
- Specific Target Organ Toxicity / Aspiration Toxicity
- Produces toxic gases in contact with water, air or acid
- Sensitising Ecotoxic (capable of exhibiting a hazardous property listed above not directly displayed by the original waste)
- Persistent Organic Pollutants

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/719394/Waste-classification-technical-guidance-WM3.pdf link to "Guidance on the Classification and Assessment of Waste", (1st Edition v1.1)

All landfill sites will have their own laws and regulations relating to what is and is not deemed acceptable. Even if the soil is inert, water content may play a significant role in where it can be used. If the material is hazardous, there will be a very limited number of places it can be disposed, and further tests would need to be carried out on potential leachates.



United States

In the United Sates there are many federal, state and local regulations governing tunnel spoil materials, including solids, liquids, gases, dusts and odours. The following discussion should be considered as a summary level of some of the overarching governance provisions for tunnel spoil handling treatment and disposal options. It has become very apparent in the Unites States that there are many complex and inter-locking, inter-agency regulations, approvals and permits needed for a successful commencement of tunnelling operations.

National Environmental Protection Act (NEPA)

The National Environmental Policy Act (NEPA) was signed into law on 01 Jan 70. NEPA requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. The range of actions covered by NEPA is broad and includes:

- Making decisions on permit applications
- Adopting federal land management actions
- Constructing highways and other publicly owned facilities

Using the NEPA process, agencies evaluate the environmental and related social and economic effects of their proposed actions. Agencies also provide opportunities for public review and comment on those evaluations.

Title I of NEPA contains a Declaration of National Environmental Policy. This policy requires the federal government to use all practicable means to create and maintain conditions under which man and nature can exist in productive harmony.

Section 102 in Title I of the Act requires federal agencies to incorporate environmental considerations in their planning and decision-making through a systematic interdisciplinary approach. Specifically, all federal agencies are to prepare detailed statements assessing the environmental impact of and alternatives to major federal actions significantly affecting the environment. These statements are commonly referred to as ***Environmental Impact Statements (EIS) and Environmental Assessments (EA).***

Title II of NEPA established the President's Council on Environmental Quality (CEQ)to oversee NEPA implementation. The duties of CEQ include:

- Ensuring that federal agencies meet their obligations under NEPA
- Overseeing federal agency implementation of the environmental impact assessment process
- Issuing regulations and other guidance to federal agencies regarding NEPA compliance.

California Environmental Quality Act (CEQA)

The California Environmental Quality Act (CEQA) is a California law that requires public agencies and local governments to evaluate and disclose the environmental impacts of development projects or other major land use decisions, and to limit or avoid those impacts to the extent feasible.

The laws and rules governing the CEQA process are contained in the CEQA statute (Public Resources Code Section 21000 and following), the CEQA Guidelines (California Code of Regulations, Title 14, Section 15000 and following), published court decisions interpreting CEQA, and locally adopted CEQA procedures

The California Environmental Quality Act is a California statute passed in 1970 and signed into law by then-Governor Ronald Reagan, shortly after the United States federal government passed the National Environmental Policy Act, to institute a state-wide policy of environmental protection. CEQA does not directly regulate land uses, but instead requires state and local agencies within California to follow a protocol of analysis and public disclosure of environmental impacts of proposed projects and, in a departure from NEPA, adopt all feasible measures to mitigate those impacts. CEQA makes environmental protection a mandatory part of every California state and local agency's decision-making process. It has also become the basis for numerous lawsuits concerning public and private projects

Once an agency determines that a proposed activity is a project under CEQA, it will usually take the following three steps:

- Determine whether the project falls under a statutory or categorical exemption from CEQA.
- If the project is not exempt, prepare an initial study to determine whether the project might result in significant environmental effects.
- Prepare a negative declaration, mitigated negative declaration, or EIR, depending on the initial study.

Most development projects fall into one of the following categories of CEQA review:

- Statutorily exempt
- Categorically exempt
- Initial Study and Negative Declaration (IS/ND)
- Initial Study and Mitigated Negative Declaration (IS/MND)
- Environmental Impact Report (EIR)

A flow chart of the CEQA process is provided below in Figure 18. For more information on how to determine whether an activity is subject to environmental review, what steps are involved in the environmental review process, and the required content of environmental documents, please refer to the CEQA Guidelines.

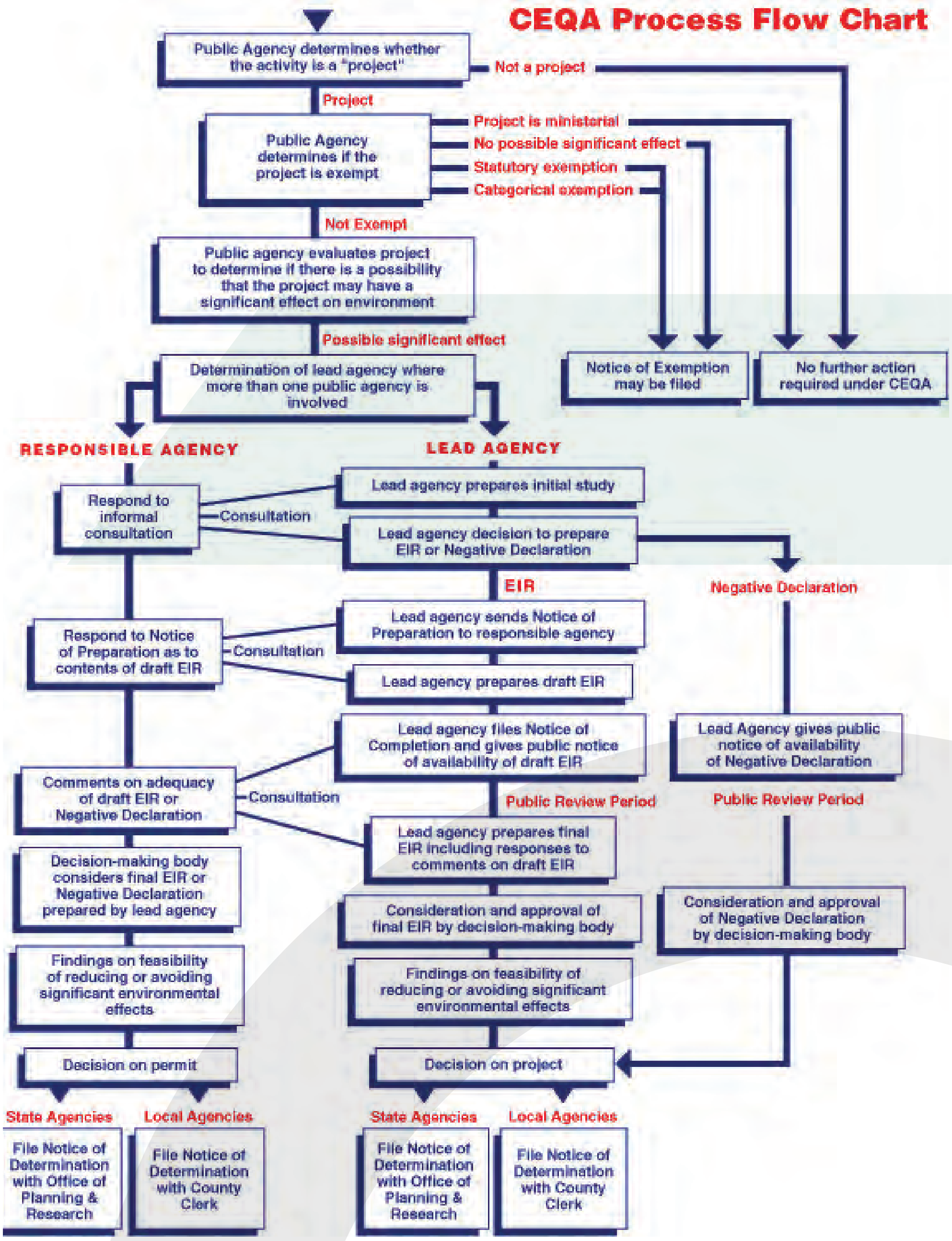


Figure 18: California Environmental Quality Act – Process Flow Chart
Summary level activity and process flow chart for CEQA permit development, application, publicity and review processing. (Courtesy of California Environmental Protection Agency)

7 >> Spoil Testing to Meet Permitting Regulations and Repurposing Assesssments

In general terms, most modern-day tunnels are governed under permit-granting agency requirements for all excavated spoil materials. This includes all solids, liquids and gases and within these classifications the following materials.

- Rock
- Soil
- Water
- Gases, vapours and dust
- Petroleum, oils and lubricants (POLs)
- Contaminated materials
- Hazardous materials

As described more fully in the following Case Studies, many agency-issued permits require specific repetitive material tests to assure full compliance with the specific terms of the approvals; i.e. quality and rates for all products of excavation. The following subsections describe specific testes performed on tunnel spoil material using elaborate procedures for;

- Bio-degradability
- Eco-toxicity

7.1 TESTS CARRIED-OUT ON SOIL SAMPLES ON-SITE

On the Santa Lucia (Italy) tunnel project referenced below in Section 8 – Case Studies and Project Examples – Excavated Spoil Material, the soil in the spoil bins were analysed for soil conditioning foam biodegradability and eco-toxicity. No soil (tunnel spoil) was removed from the site before it was in full compliance with all regulations. The bio-degradability was tested as shown below in Figure 19.

The eco-toxicity toxicity tests and equipment on the bio-luminescent bacteria Vibro Fisheri according to ISO 11348-3:2007 are shown below in Figures 20 and 21.

This would probably be considered to be the one of the projects in the world that has taken great responsibility of environmental responsibility to a higher level.

Figure 19: Eco-Toxicity Test Equipment
Equipment for testing eco-toxicity levels on soil conditioning foam from tunnel spoil samples.

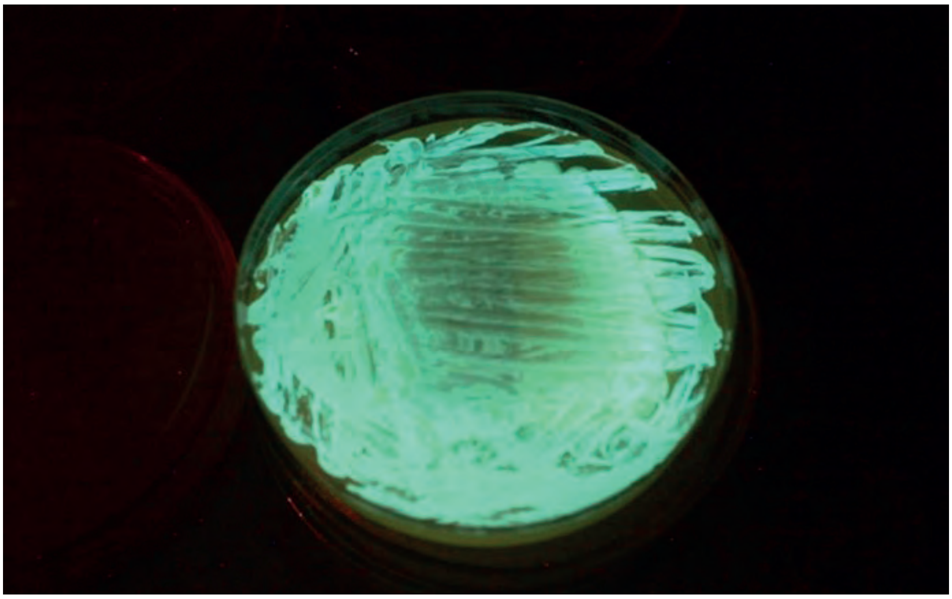


Figure 20: Eco-Toxicity Test Equipment
Equipment for testing eco-toxicity levels on soil conditioning foam from tunnel spoil samples.

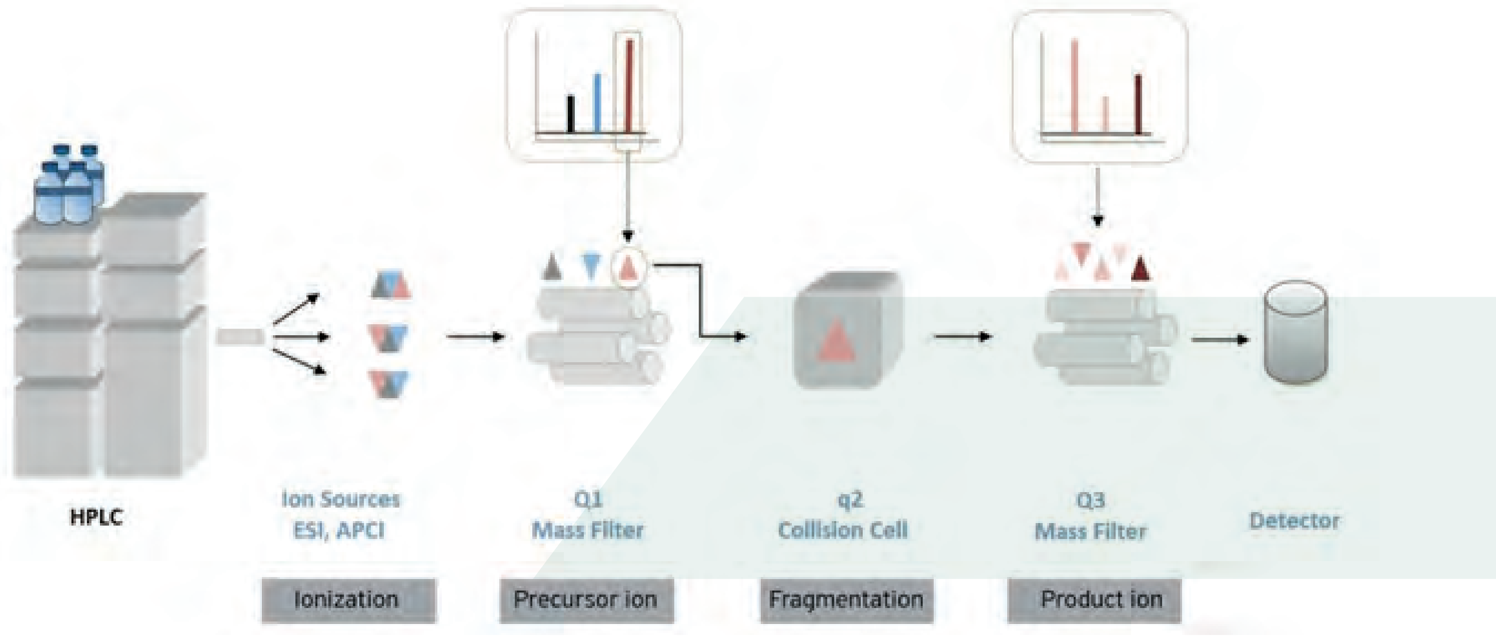


Figure 21: Biodegradability Test Process Flow Chart – Soil Conditioning Foams
General arrangement process flow chart for testing biodegradability rate(s) on soil conditioning foam from tunnel spoil samples produced on the Santa Lucia Tunnel Project in Italy.

7.2 MATERIAL TESTS TO CONFIRM SITE SUITABILITY OF TUNNEL SPOIL MATERIAL

German Water Hazard Class (WGK) for Substances and Mixtures certification is one of the most complete and strict analyses that can be carried-out on materials to be used in a tunnel. Please reference Section 15 – References and Additional Reading Materials. This analytic approach is separated into three categories.

- WGK=1 Low Impact
- WGK=2 Medium Impact
- WGK=3 High Impact

The tests are a combination of measuring the eco-toxicity to mammals, fishes, algae, Daphna and its biodegradability curve measured over 28 days.

Eco-toxicity and bio-degradability tests can be taken one stage further after that. Please refer to Figures 22 and 23. Different products from different suppliers can be tested so that the safest, least damaging to the environment can be chosen to perform the task. Of course, the material would also need to satisfy the technical requirements.

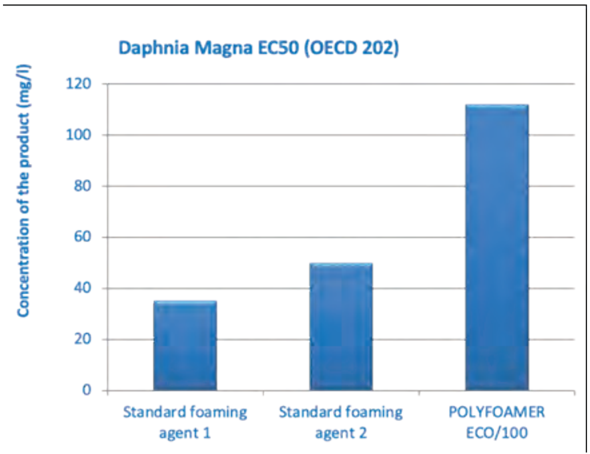


Figure 22: Eco-Toxicity Test Results – Conditioner
Eco-toxicity (Daphnia Magna) test results of soil conditioning foam typically used in EPB tunnelling operations but could also be used for dust suppression and control.

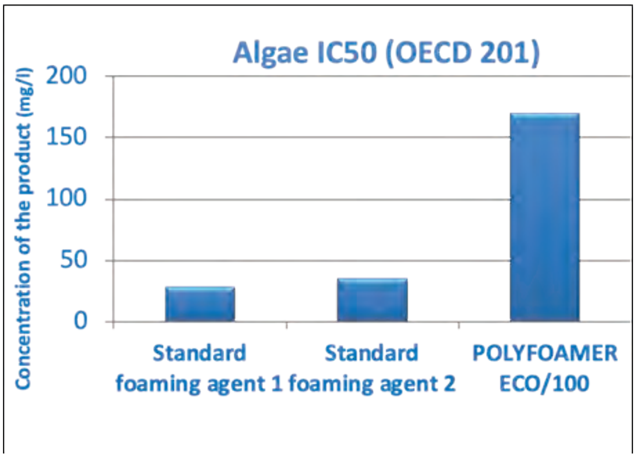


Figure 23: Eco-Toxicity Test Results – Conditioner
Eco-toxicity (algae IC50) test results of soil conditioning foam typically used in EPB tunnelling operations but could also be used for dust suppression and control.

8 >> Case Studies and Project Examples – Excavated Spoil Materials

As noted in Section 3.1, the report authors and contributors developed several Case Studies for the handling, treatment and final disposal options for tunnel spoil materials; including solids, liquids and gases as products of the excavation. These Case Studies are but a small sampling of projects executed in recent years, both completed and still underway. Additional and more challenging Case Studies would include tunnel and underground construction projects that have been deferred or substantially delayed pending final satisfactory resolution of excavation spoil issues. Indeed, the longer and more publicly challenged projects need comprehensive soil handling planning and program management clearly built into the very early stages of project development.

The following Case Studies are generally well-known projects that provided good example of a high standard of care for tunnel spoil management challenges and solutions from around the globe.

Figure 24: Santa Lucia Tunnel Boring Machine
Fully assembled Earth Pressure Balanced TBM on-site for the Santa Lucia tunnel project in Italy.

Figure 25: Santa Lucia Tunnel Spoil Storage Area
Pre-construction appearance of the walled spoil storage area for the Sant Lucia Tunnel Project.

8.1 SANTA LUCIA TUNNEL PROJECT (ITALY) – EXCAVATION SPOIL HANDLING AND TREATMENT

The Santa Lucia tunnel is a part of the A1 Autostrada between Milan and Naples. The TBM was 15.96m diameter and the drive was 7.55 km (4.7 miles) long. Please refer to Figures 24 and 26 below. Prior to the drives commencing, the Client was insistent upon the fact that all excavated soil was as "pure" as the in-situ soil before being allowed to leave the job site. To this end, it was decreed that all products used on the TBM to aid the excavation process were to be analysed at Politecnico di Torino, for the technical tests, and at the CNR (National Research Council), for their environmental impact, and the best products would be used to affect the excavation. As result of the technical and environmental tests, only one product (the Polyfoamer ECO/100) was approved for the use during the TBM excavation, being the one with the lowest impact to the spoil at the dosage necessary to condition the soil.

Storage bins (figure 25) for the spoil were built on the jobsite to temporarily hold the spoil until the ground conditioning products within it had biodegraded back to an inert, non-toxic state, representative of the soil prior to having been excavated. These spoil containment structures were truly immense, considering the size of machine and anticipated TBM advance rates. The spoil held within the bins had to be tested to prove its suitability prior to being sent away from the jobsite. The TBM excavated more than 3.5 million tonnes.

Foaming agents available in the TBM industry differ significantly not only from a technical point of view, but also from their environmental characteristics which depend on the product biodegradability (important to describe the persistence of a foaming agent along time) and its toxicity to terrestrial and watery organisms. Both biodegradability and eco-toxicity of the soil conditioning products ought to be evaluated and analysed to have a complete data summary of chemical products and potential environmental impacts. All these environmental properties can be quantified with tests following the Organisation for Economic Cooperation and Development International Guidelines and Standards (i.e. OECD, 2000 and OECD, 2005) and it is recommended and valuable for a TBM project to quantify the products impact from independent and accredited institutes or laboratories.

Detailed functional profile of the Earth Pressure Balanced TBM and initial portion of the trailing gear showing primary equipment layout. (Courtesy of Herrenknecht AG)

For more and more TBM projects the environmental impact of the "spoil" is becoming a target for the selection of the conditioning agents and so the biodegradability and eco-toxicity of the chemical products must be well known before the TBM start.

The most complete analysis to investigate the environmental features of a chemical product include toxicity tests for several organisms (mammals, fishes, algae and daphnia) and evaluation of biodegradability curve:

- Oral and cutaneous toxicity towards mammals
- Toxicity towards watery and terrestrial organisms, such fish, algae, crustaceous, etc
- Biodegradability curve:
  - Measured in the first 28 days
  - According to OECD 301 method (OECD, 2000)

The eco-toxicological data are expressed with some indexes like LC50, EC50, etc., which represent the concentration of product in water necessary to produce "and effect" to the 50% of the organisms' population used for the tests (mammals, fishes, daphnia, algae, etc.). According on the different regulations, this "effect" can mean to block the growth of the organisms, stop their reproduction, etc.

If compared with traditional foaming agents, the eco-toxicity of the new Polyfoamer ECO line products is extremely lower (Figures 27 and Figure 28).

The bio-degradability of the foaming agents is evaluated considering two indexes:

- COD (Chemical Oxygen Demand): the amount of oxygen which can be consumed by chemical reactions in a defined system (chemical product, solution, conditioned soil, etc).
- BOD (Biochemical Oxygen Demand): the amount of dissolved oxygen demanded by aerobic biological organisms to break down organic compound in a given sample at certain temperature over a specific time-period.

The biodegradability of a product at a defined time is indicated as a percentage of the BOD at that stage over the COD of the system: chemically it means how much oxygen is consumed compared to the total available for chemical reactions.

Even if the biodegradability value is of mandatory importance, also the BOD at a specific time (i.e. 28 days according to OECD 301 C) must be considered to define the environmental properties of a chemical product (see Figure 29). Lowest is BOD and lowest is the "effort" for chemical reactions to consume the oxygen in the system.

The biodegradability and eco-toxicity of the foaming agents are very important for the selection of the products with the lowest environmental impact even though they are not enough for a "well-done" decision about the conditioning products for a TBM project. Even more attention should be paid to the environmental impact of the conditioned soil planning its re-use as by-product according to the project area regulations and restrictions reducing the environmental impact of the civil work and avoiding extra-costs for the Contractor.

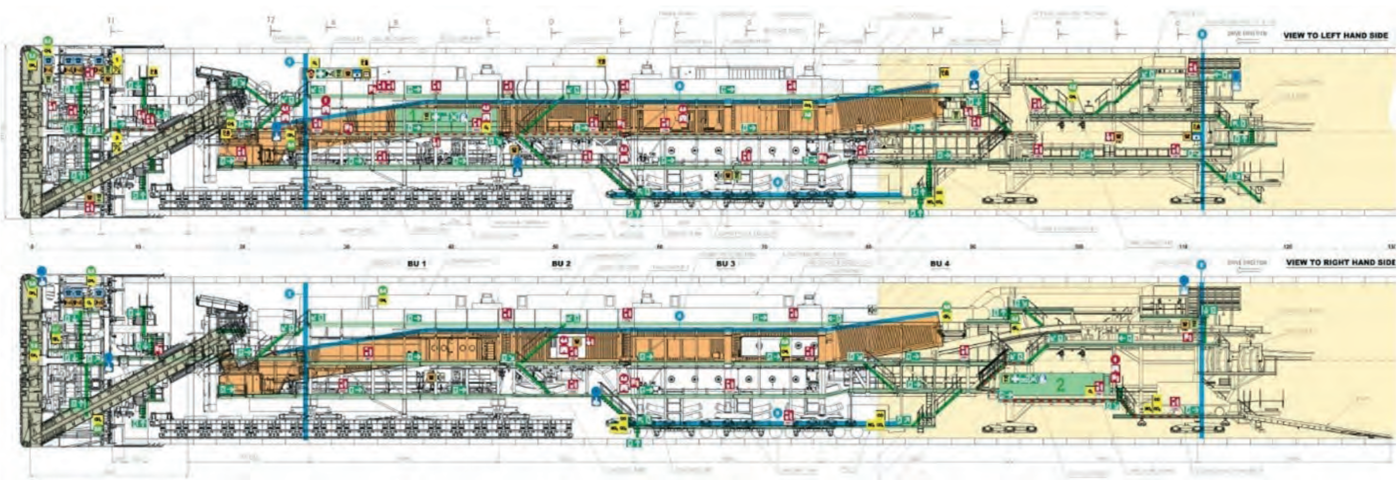


Figure 26: General Arrangement Profile of the Santa Lucia TBM

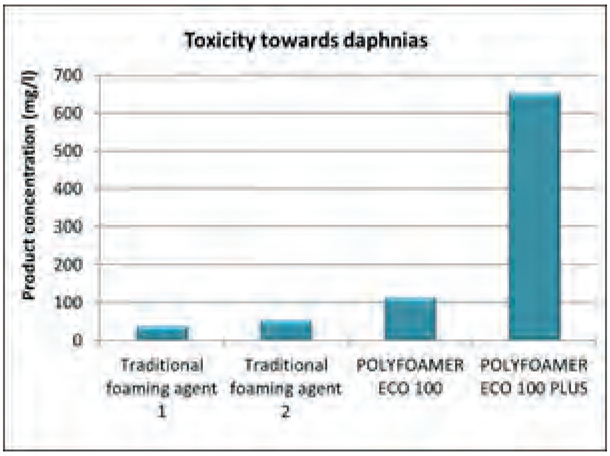


Figure 27: Eco-Toxicity Test Results – Conditioner
Eco-toxicity (Daphnia Magna) test results of several soil conditioning foams typically used in EPB tunnelling operations.

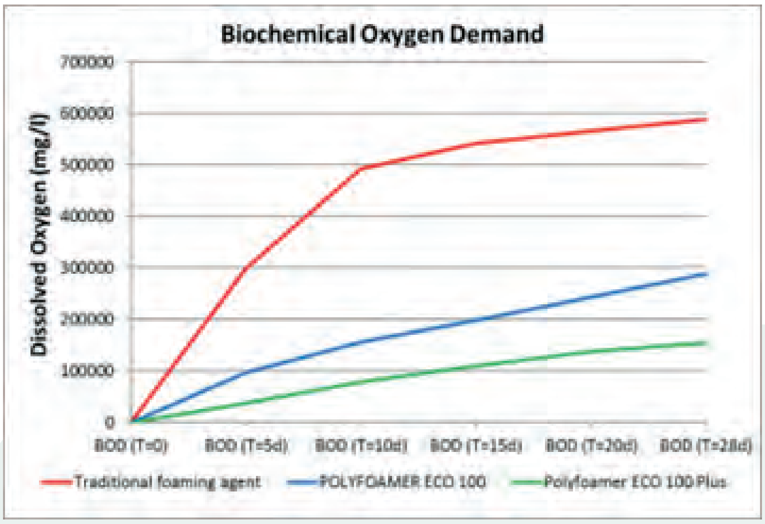


Figure 29: Biochemical Oxygen Demand
Biochemical oxygen demand during the TBM excavation process and spoil disposal operations using various spoil conditioning foaming agents.

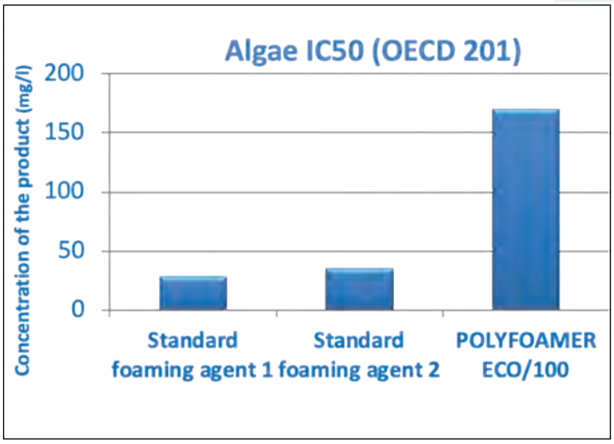


Figure 28: Eco-Toxicity Test Results – Conditioner
Eco-toxicity (algae IC50) test results of several soil conditioning foams typically used in EPB tunnelling operations.

8.2 ARROWHEAD TUNNELS PROJECT (USA) – EXCAVATION SPOIL HANDLING AND TREATMENT

The Arrowhead Tunnels Project was constructed near San Bernardino, California, USA between 2003 and 2009. This was a very geotechnically challenging tunnel in its day because of highly variable ground conditions as more fully described below. The key data and statistics for the project are listed below in Table 4.

The Arrowhead Tunnels Project location as shown below in Figures 30 and 31 is in an region that for decades has been utilized for major water conveyance projects used to supply the expanding Los Angeles area.

The Arrowhead Tunnel Project produced 343,236 m³ (448,610 yd³) of excavated tunnel spoil using two hybrid hard rock TBM. The TBMs were equipped with substantial pre-excavation drilling and grouting equipment and systems that were considered state-of-the-art (at the time) and were also considered essential for successful tunnelling within the anticipated difficult (highly variable) ground and groundwater conditions. All equipment and spoil were configured for an average tunnel excavation advance rate of 15.8 m/day (52 feet/day) per TBM. Table 4 above summarizes the estimated quantities and rates.

ARROWHEAD TUNNEL PROJECT – DATA SUMMARY				
LENGTHS			**PROJECT DATA**	
East Tunnel West Tunnel	6,840m 6,062m	(22,441 LF) (19,888 LF)	Year built Owner Location Contractor	2003 to 2009 Metropolitan Water District (MWD) San Bernardino, California, USA Shea-Kenny JV
DIAMETER			**GROUND TREAT**	
Excavated Final Lining	5.82m 4.87m	(19’-1”) (16’-0”)	Pre-excavation drilling and grouting Probing and drainage holes	
SPOIL EXCAVATED			**PERMITS REQ’D**	
East Tunnel West Tunnel	181,967 m³ 161,269 m³	(237,830 yd³) (210,780 yd³)	USFS CEQA	Tunnel water inflows limitations Treated water discharge to streams
GROUNDWATER HEADS				
East Tunnel West Tunnel	275m 180m	(900 feet) (600 feet)		

Figure 30: MWD Inland Feeder Project
General arrangement plan of the Arrowhead Tunnels Project within the Inland Feeder.

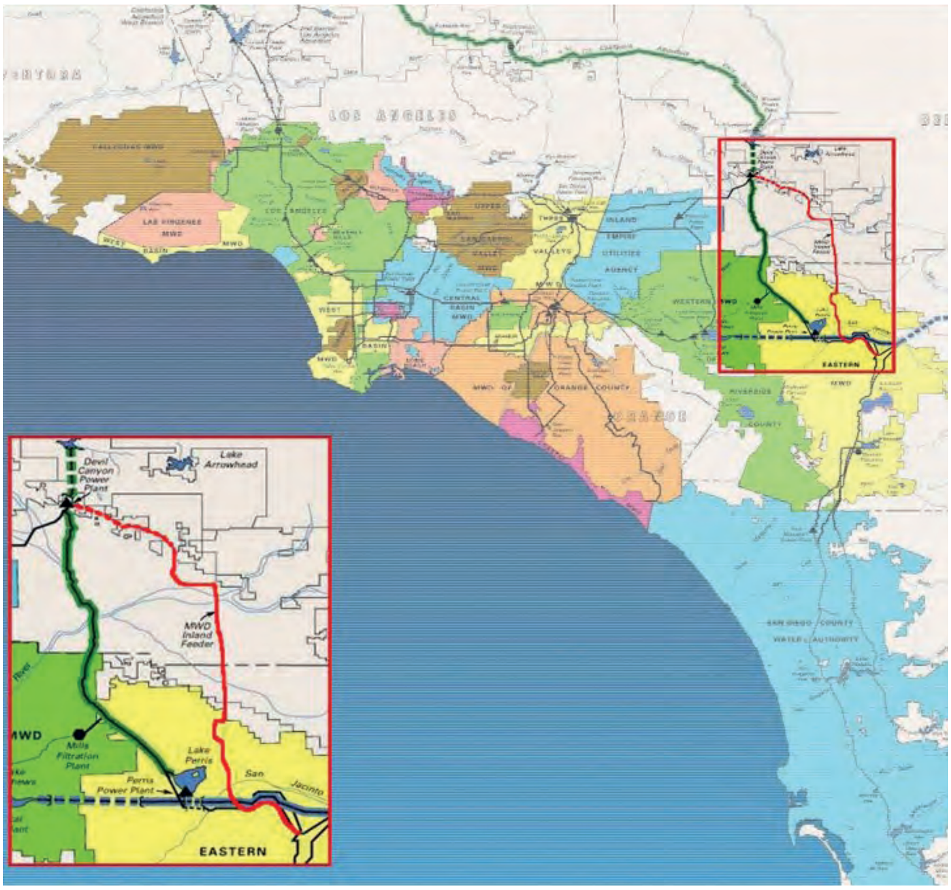


Figure 31: Southern California Regional Map
Regional map of Southern California showing Los Angeles and San Bernardino; site of the Arrowhead Tunnels Project.

8 >> Case Studies and Project Examples – Excavated Spoil Materials

ITEM	TUNNEL ATTRIBUTES	STRAWBERRY TUNNEL		WATERMAN TUNNEL		TOTALS (OR AVERAGES)	
		METRIC	IMPERIAL	METRIC	IMPERIAL	METRIC	IMPERIAL
A	TUNNEL DATA						
1	Tunnel length	6,840m	22,441 ft	6,062m	19,888 ft	12,902m	42,329 ft
2	Excavation diameter	5.82m	19’-1”	5.82m	19’-1”		
3	Excavation linear quantities	26.6 m^3/m	10.6 yd^3/ft	26.6 m^3/m	10.6 yd^3/ft	26.6 m^3/m	10.6 yd^3/ft
4	Excavation quantities	181,967 m^3	237,830 yd^3	161,269 m^3	210,780 yd^3	343,236 m^3	448,610 yd^3
5	Estimated Swell Factor	1.20	1.20	1.20	1.20	1.20	1.20
6	Estimated Loose volume	218,360 Lm^3	285,400 Lyd^3	193,520 Lm^3	252,940 Lyd^3	411,880 Lm^3	538,340 Lyd^3
B	TUNNEL EXCAVATION						
1	Estimated excavation rates	15.8 m/day	52 ft/day	15.8 m/day	52 ft/day	15.8 m/day	52 ft/day
2	Actual excavation rates	7.0 m/day	23 ft/day	6.4 m/day	21 ft/day	6.7 m/day	22 ft/day
3	Estimated groundwater inflows	1,135 l/min	300 gpm	1,325 l/min	350 gpm	1,230 l/min	325 gpm
4	Actual groundwater inflows	1,325 l/min	350 gpm	1,700 l/min	450 gpm	1,515 l/min	400 gpm

Table 4: Arrowhead Tunnels – Dimensions and Quantities
Summary of the tunnel excavation quantities encountered for the Strawberry and Waterman Tunnels as part of the Arrowhead Tunnels Project.

Figure 32: Arrowhead Tunnels – Tunnel Spoil Cars
Typical arrangement of the tunnel spoil transport (muck cars) staged in portal area before dumping.

Figure 33: Arrowhead Tunnels – Spoil Treatment
Overland conveyor, vertical clarifier and centrifuge installed at the tunnel portal area.

8 >> Case Studies and Project Examples – Excavated Spoil Materials

8.2.1 TUNNEL SPOIL HANDLING AND TREATMENT SYSTEMS

Based on the tabular information above, approximately 343,236 m^3 (448,610 yd^3) in-situ volume was excavated from the two tunnels using rail-mounted muck cars as shown above in Figure 32. A portion of the solids separation plant is shown above in Figure 33. All had to be handled, treated and properly disposed of over a four-year excavation schedule. The primary tunnel spoil handling equipment and systems included the following, starting at the TBM cutterhead.

Solid Materials – Bulk, Dry Material Handling System

- Tunnelling Boring Machines (two each)
  - Screw auger (need for material conveyance only)
  - Primary conveyor
  - Secondary conveyor
- Tunnels and Portal Haulage (two locations)
  - Muck cars (15 m^3/each (20 yd^3)); rail mounted with diesel locomotives
  - Roll-over muck car dump
  - Muck hopper and reclaim conveyor
  - Muck hopper discharge conveyor
  - Overland conveyor (to stockpile)
- Off-Site Equipment (two fleets)
  - Front-end loaders
  - Over the road haul trucks

Fluidized Materials – Hydraulic Conveyance Systems

- Tunnelling Boring Machine (two each)

- Slurry water recirculation system
- Make-up water supply and measurement system
- Water + slurry collection points
- Habermann slurry pump (hydraulically powered)
- Warman slurry pump (electrically powered)

- Tunnels and Portal Conveyance (two locations)
  - Tunnel water slurry discharge pipeline
  - Tunnel water slurry recirculation pipeline
  - In-line Warman slurry pumps (electrically powered)
- On-Site Solids Separation Plant and Equipment (two plants)
  - Screens and cyclones large particle (>25mm (1”)) extraction at tunnel portal
  - Vertical clarifiers small and medium (sand sized) particle extraction
  - Centrifuges fine (silt sized) particle extraction
  - Flow controls volumetric data loggers for continuous readings

The process flow chart illustrated below in Figure 34 summarizes the plant and equipment utilized for handling, treating and final disposal (multiple options) of the spoil material originating from the Arrowhead Tunnels Project.

As shown above in Figure 34, the equipment and system diagram, considerable equipment units and material handling phases were required to successfully transport both dry (bulk) and wet (slurry) tunnel spoil mechanically and hydraulically from the tunnel face to the final point of disposal at various on and off-site locations. The summary below in Table 5 lists the general arrangements and capacities of specific equipment units incorporated into the spoils handling system.

Key features of the hydraulic slurry handling system utilized for the Arrowhead Tunnel included the following.

- Slurry handling and separation system designed and installed due to excess fines (sand and silt) materials in the spoil in TBM plenum; resulting in severe clogging issues.
- Capable to handle up to 15% fines (by weight) using a water slurry system to the portal.
- Pumps included both Habermann and Warman slurry pumps for up to 6,860m (22,500 LF) distance per tunnel.
- Slurry system utilizes Yellow Mine Pipe (only) to convey slurry. Wear was minimal.

Figure 35 illustrates an interior cross-sectional view of the hybrid TBM used on the project that was subsequently modified (and further adapted) to include a spoil slurry (water based) conveyance system.

Treatment of the tunnel spoil was only accomplished mechanically and utilized periods of natural air drying. No chemicals or remixing was performed before final disposal on-site or haul to various off-site location(s). Final disposal of tunnel spoil fell into two distinct categories: on-site engineered fills and off-site landfills and engineered fills and structures.

- On-Site (avoiding extensive trucking)
  - Infilling of nearby mountain valley
  - Staging area pad building for the Owner’s future needs
- Off-Site (requiring load-out and extensive trucking)
  - Municipal land fills
  - Commercial building foundation pad developments
  - Topping-out local area levees and flood control berms including sediment basins

Due to the nature of the tunnel spoil, whether mechanically or hydraulically transported from the tunnel spoil, was not considered suitable for any of the following secondary uses, manufacturing, or repurposing opportunities.

- Concrete aggregates
- Chemically or thermally processed into other end products

While the tunnel spoil (bulk-dry and slurry-wet) had not been treated (or tainted) with any chemicals including bentonite, the consistent fines (>200 mesh) content (passing 0.074mm (0.0029 inch) was very high, largely due to its original “altered” geological conditions and after multiple handling and screening stages.

The final material character (grain size distribution) just prior to off-site disposal, was generally less than 40mm (1.5 inch) for the majority of the entire excavated tunnel lengths, with a large percentage found to be less than 20mm (0.75 inch).

Conclusions

Virtually all tunnel spoil material was environmentally disposed of without the use of chemicals or any secondary processing. Overall, the handling, treatment and final disposal of 13 km (8.1 miles) and 343,236 m^3 (448,610 yd^3) of tunnel spoil material was considered a great success as considered from environmental, commercial and social considerations. Additionally, there were no residual quantities or impacts remaining related to tunnel spoil materials at the end of the project.

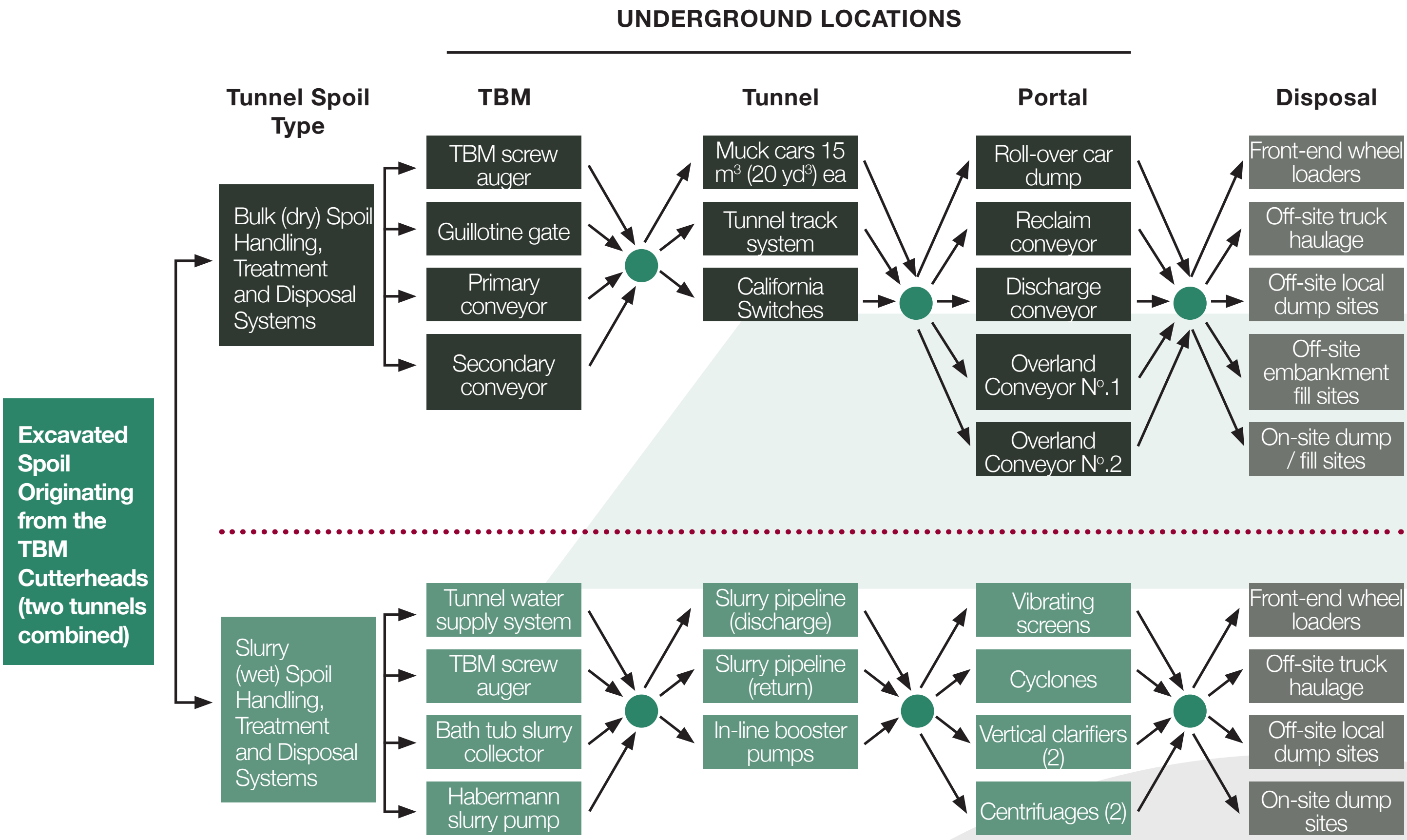


Figure 34: Arrowhead Tunnels Project – Process Flow Chart for Tunnel Spoil Materials
Bulk (dry) and slurry (wet) spoil handling process chart, equipment and plant units utilized on the Arrowhead Tunnels Project muck handling, treatment, conveying and disposal systems.

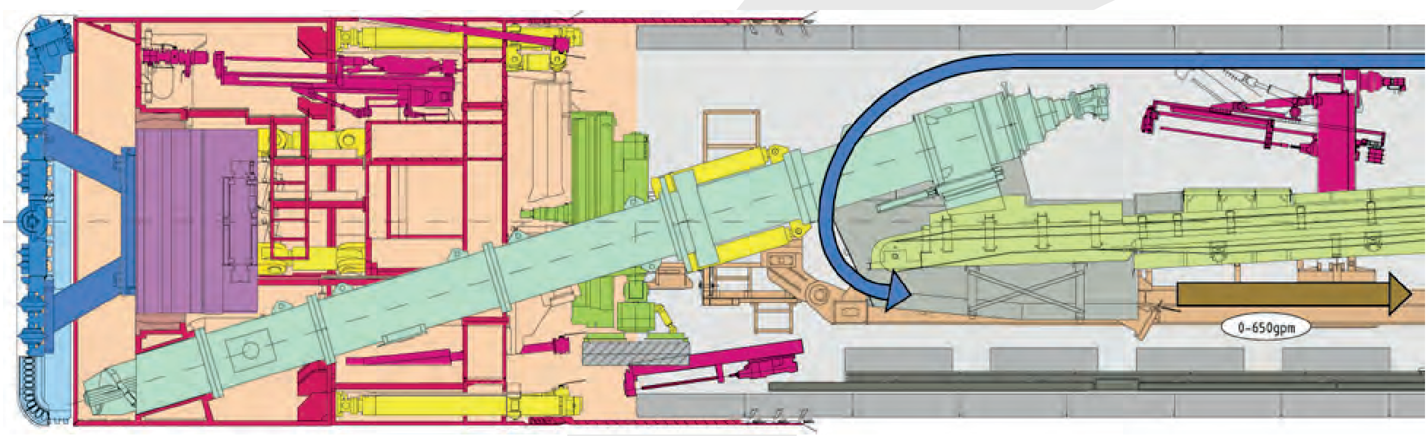


Figure 35: Arrowhead Tunnels Project – Interior Schematic of the TBM Hydraulic Conveyance System
General arrangement of the hydraulic (wet) spoil handling equipment units utilized within the confines of the hard rock TBMs. (Courtesy of Herrenknecht AG).

8 >> Case Studies and Project Examples – Excavated Spoil Materials

ITEM	TUNNEL ATTRIBUTES	STRAWBERRY TUNNEL		WATERMAN TUNNEL		TOTAL	
		METRIC	IMPERIAL	METRIC	IMPERIAL	METRIC	IMPERIAL
A	**TBM COMPONENTS**						
1	**Screw Auger** Diameter Length Power	700mm 14m 160 kW	2'-4" 46 feet 215 HP	700mm 14m 160 kW	2'-4" 46 feet 215 HP		
2	**Primary Conveyor** Width Length Power	750mm 20m 45 kW	30 inches 70 feet 60 HP	750mm 20m 45 kW	30 inches 70 feet 60 HP		
3	**Secondary Conveyor** Width Length Power	750mm 20m 60 kW	30 inches 70 feet 80 HP	750mm 20m 60 kW	30 inches 70 feet 80 HP		
B	**TUNNEL HAULAGE**						
1	**Muck Cars (tunnel track)** TBM push (1.5m; 5 ft) bank TBM push (1.5m; 5 ft) loose Muck car capacity (nominal) Muck car capacity (peak)	40 m^3 48 m^3 12 m^3 15 m^3	52 yd^3 63 yd^3 15.6 yd^3 19.5 yd^3	40 m^3 48 m^3 12 m^3 15 m^3	52 yd^3 63 yd^3 15.6 yd^3 19.5 yd^3		
	Muck car train composition	5 cars each train		5 cars each train		5 cars each train	
2	**Roll-Over Dump (portal)**						
	Muck car capacity	1 each		1 each		1 each	
	Hopper capacity	32 m^3	25 yd^3	32 m^3	25 yd^3		
3	**Reclaim Conveyor (roll-over)** Width Length Capacity	900mm 15m 310 m^3/hr	36-inches 50 feet 400 yd^3/hr	900mm 15m 310 m^3/hr	36-inches 50 feet 400 yd^3/hr		
4	**Overland Conveyor No.1** Width Length Capacity	900mm 60m 310 m^3/hr	36-inches 200 feet 400 yd^3/hr	900mm 60m 310 m^3/hr	36-inches 200 feet 400 yd^3/hr		
5	**Overland Conveyor No.2** Width Length Capacity			900mm 160m 310 m^3/hr	36-inches 500 feet 400 yd^3/hr		
C	**HYDRAULIC SPOIL HANDLING**						
1	**Habermann pump (TBM)** Capacity Pressure	41.0 l/sec 1.4 MPa	650 gpm 200 psi	41.0 l/sec 1.4 MPa	41.0 l/sec 1.4 MPa		
2	**Warman in-line slurry pumps** Capacity Pressure	63.1 l/sec 1.4 MPa	1,000 gpm 200 psi	63.1 l/sec 1.4 MPa	1,000 gpm 200 psi		
3	**Solids Separation Plants** Cyclone + screens Vertical clarifier Centrifuge	62.1 l/sec 25.2 l/sec 6.3 l/sec	1,000 gpm 400 gpm 100 gpm	62.1 l/sec 25.2 l/sec 6.3 l/sec	1,000 gpm 400 gpm 100 gpm		

Table 5: Arrowhead Tunnels – Tunnel Spoil Handling Systems
Summary of the TBM, tunnel and portal spoil handling systems for both dry (bulk) and wet (slurry) systems and equipment for the Strawberry and Waterman Tunnels as part of the Arrowhead Tunnels Project.

8.3 SECOND AVENUE SUBWAY (USA) – EXCAVATION SPOIL HANDLING AND TREATMENT

The Second Avenue Subway Project was constructed in New York City between 2008 and 2016. The project consisted of several separate station and tunnel contracts as listed below and benefited from very favourable hard rock conditions encountered at shallow depths as shown below in Figures 36 and 37.

- 63rd Street Station
- 72nd Street Station and Tunnels Project
- 86th Street Station
- 96th Street Station
- Running tunnels Contract (63rd to 96th Streets)

The 72nd Street Station and Tunnels Project was constructed between 2010 and 2013. This was a very challenging project in its day because of the location in the highly developed and densely populated Upper East Side area of New York City. The ground and groundwater conditions, however, were very favourable for underground construction. The key data and statistics for the project are listed below.

Groundwater issues were virtually non-existent due to the granitic / schistose nature of the ground in all areas of subsurface excavation. Please see a separate discussion in Section 9 for groundwater and construction water handling, treatment and disposal.

The general configuration of the 72nd Street Station and Tunnels Project (for example) was a combination of shafts, tunnels and caverns covering a distance of 915m (3,000 LF) and located between 63rd and 73rd Streets under Second Avenue in Manhattan, New York City. A summary of the key dimensions and quantities details are listed below in Table 6 for reference.

NYC – SECOND AVENUE SUBWAY – 72ND STREET STATION AND TUNNELS PROJECT – DATA SUMMARY				
LENGTHS – CAVERNS			**PROJECT DATA**	
Station & Cross-Overs G3 Turn-Out G4 Turn-Out 63rd Street (stacked)	398m 65m 113m 50m	(1,305 LF) (210 LF) (370 LF) (165 LF)	Year built Owner Location Contractor	2010 to 2013 Metropolitan Transportation Authority New York City, New York, USA Schiavone-Shea-Kiewit, JV
LENGTHS – TUNNELS			**GROUND TREATMENT**	
Horseshoe – exc'd Concrete lined	130m 1,220m	(410 LF) (4,000 LF)	Pre-excavation drilling and grouting Probing and drainage holes	
SECTIONS – CAVERNS			**GROUND SUPPORT**	
Station & Cross-Overs G3 Turn-Out G4 Turn-Out 63rd Street (stacked)	137 m² 32.5 m² 32.5 m² 37.0 m²	(1,470 ft²) (350 ft²) (350 ft²) (400 ft²)	**Initial Support** Shotcrete, resin-grouted rock bolts and dowels **Final Lining** Reinforced concrete	
SPOIL EXCAVATED			**GROUND STRATA**	
Caverns Tunnels Entrances Cross-Passages/ adits	95,700 m³ 2,300 m³ 11,490 m³ 3,830 m³	(125,000 yd³) (30,000 yd³) (15,000 yd³) (10,000 yd³)	Granitic with Manhattan Schist Few faults, brecciated zones present **GROUNDWATER LEVELS** Caverns:	 30m (100 feet)

Figure 36: New York City Second Avenue Subway – Plan General arrangement plan of the Second Avenue Subway construction phases in New York City. (Courtesy of NYC-MTA).

Figure 37: Phase 1 – Second Avenue Subway Initial Phase 1 construction portion of the Second Avenue Subway. (Courtesy of NYC-MTA.

ITEM	DESCRIPTION	EXC'N	EXCAVATION LOCATION AND DESIGNATION						
			ARCH	BENCH	INVERT	DRAINS	DUCTS	VAULTS	SUMP
A	**SHAFTS, SUMPS AND VAULTS**								
1	South Access Shaft	D & B		•					
2	North Access Shaft	D & B		•					
3	South vault	D & B						•	
4	North sump	D & B							•
B	**TUNNELS AND ADITS**								
1	Cross-Passage (1 only)	D & B	•						
2	G3 Horseshoe Tunnel	D & B	•						
3	Entrance 1 – access adit	D & B	•						
4	Entrance 1 – access incline	D & B	•						
5	Entrance 2 – access adit	D & B	•						
6	Entrance 2 – access incline	D & B	•						
7	Entrance 3 – access adit	D & B	•						
8	Entrance 3 – emergency adit	D & B	•						
C	**CAVERNS**								
1	Station platform (train room)	D & B	•	•	•	•	•	•	•
2	North Cross-Over	D & B	•	•		•	•	•	
3	South Cross-Over	D & B	•	•		•	•	•	
4	G3 Turn-Out Cavern – north	D & B	•		•	•			
5	G3 Turn-Out Cavern – south	D & B	•		•	•			
6	G4 Turn-Out Cavern – north	D & B	•		•	•			
7	G4 Turn-Out Cavern – south	D & B	•		•	•			
8	63rd Street Cavern	D & B	•	•	•				

Table 6: Second Avenue Subway – 72nd Street Station and Tunnels Excavation Scopes.
Summary of the excavation scopes and locations within the 72nd Street Station and Tunnels project that also included three separate entrances, two cross-over caverns in additional to two turn-out caverns and adits.

8.3.1 EXCAVATION SPOIL HANDLING AND TREATMENT SYSTEMS

Virtually all excavations were performed in hard rock conditions; in granite, schist and gneissic formations using drill and blast methods as shown below in Figures 38 and 39. As a result, approximately 137,720 m3 (180,000 yd^3) of in-situ spoil was produced based on "neat-line" measure, plus approximately 20% additional spoil due to over-break excavation. All shaft, tunnel and cavern spoil materials were handled and disposed in the manner listed below in Table 7.

A unique spoil material handling system was designed and constructed for the project. It was needed to suit very confined site conditions and a restrictive operational schedule. This facility is shown below in Figure 40. This facility (Muck House) could handle and load-out as many as 120 truckloads in a permit- restricted 15 hours per day work period.

The process flow chart illustrated below in Figure 41 summarizes the plant and equipment utilized for handling, treating and final disposal (multiple options) of the rock and water spoil material originating from the Second Avenue Station and Tunnels Project. It also summarizes the tunnel wastewater handling and treatment before final disposal into the New York City sewer system.

Figure 38: Second Avenue Subway – Adit
Drill and blast operations at a full-face an Entrance adit connected to the Station Cavern.

Figure 39: Second Avenue Subway – Station Cavern
Lower-level drill and blast operations in the Station Cavern. Some invert concrete has commenced.

ITEM	DESCRIPTION	LOCATIONS – EXCAVATION OPERATIONS AND SPOIL DISPOSAL SITES		
		UNDERGROUND	SURFACE	OFF-SITE
1	Shafts, Deep Sumps and Vaults	• Hydraulic excavator • Muck boxes; 4 m^3 (5 yd^3) • Shaft crane for hosting	• Shaft crane for hosting • Front-end wheel loader • 10-wheeled dump trucks	• Commercial pad developments • Municipal land fills • Embankments
2	Tunnels and Adits	• LHD rubber-tired scooptram • Hydraulic excavator • Hydraulic demolition hammer • Muck boxes; 20 m^3 (25 yd^3)	• Muck boxes; 20 m^3 (25 yd^3) • Shaft hoist and storage house • 10-wheeled dump trucks	• Commercial pad developments • Municipal land fills • Embankments
3	Caverns, Niches and Alcoves	• LHD rubber-tired scooptram • Hydraulic excavator • Hydraulic demolition hammer • Muck boxes; 20 m^3 (25 yd^3)	• Muck boxes; 20 m^3 (25 yd^3) • Shaft hoist and storage house • 10-wheeled dump trucks	• Commercial pad developments • Municipal land fills • Embankments

Table 7: Second Avenue Subway – 72nd Street Station and Tunnels Excavation Methods
Summary of the excavation methods and locations within the 72nd Street Station and Tunnels project that also included three separate entrances, two cross-over caverns in additional to two turn-out caverns and adits.

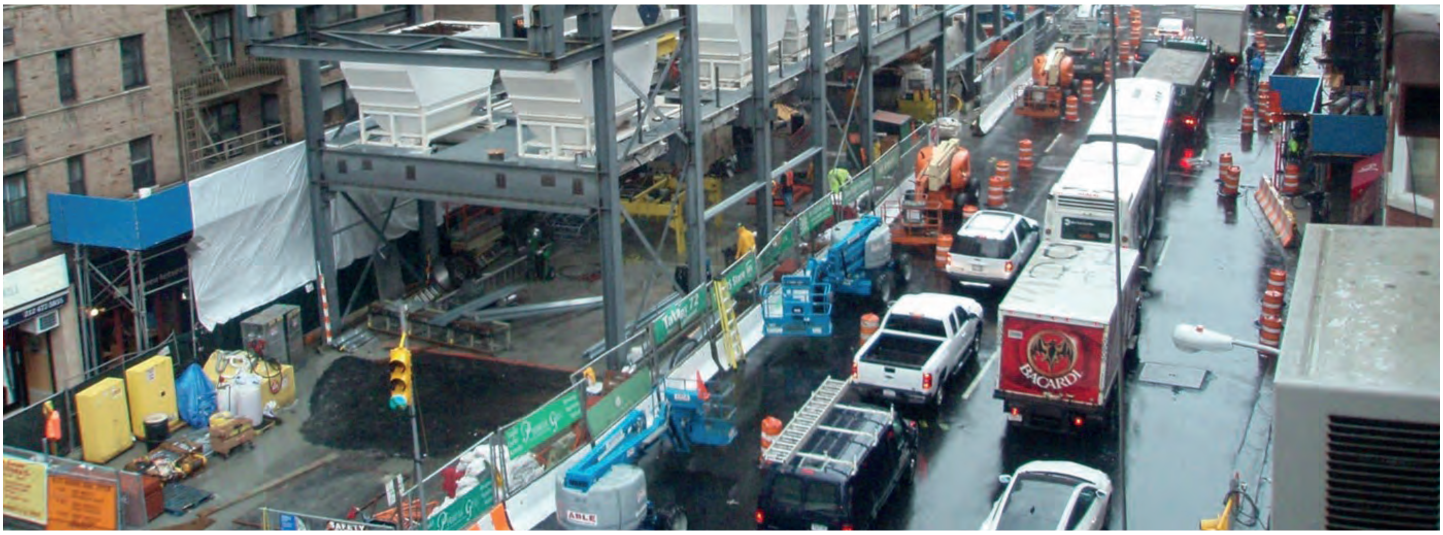


Figure 40: Second Avenue Subway – Surface Spoil Handling and Storage Facilities
Construction of one of two surface spoil handling and storage facilities installed in Second Avenue. The hoisting shaft was located below and at the far end of the structural enclosure.

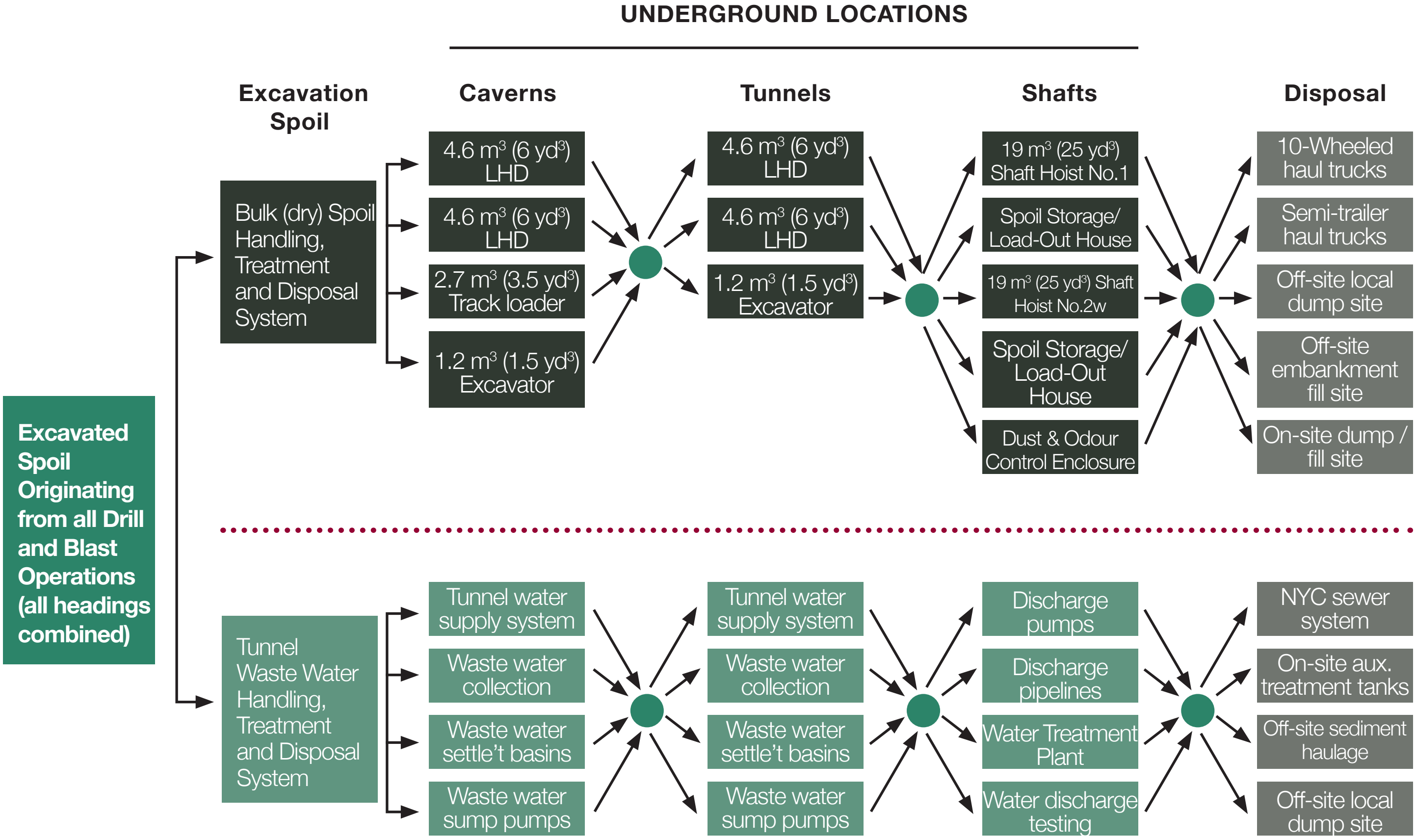


Figure 41: Second Avenue Subway Project – Process Flow Chart for Tunnel Spoil Materials
Bulk (dry) drill and blast spoil and wastewater handling process chart showing the equipment and plant units utilized. Additional products of excavation included dust and odours (ammonia).

8 >> Case Studies and Project Examples – Excavated Spoil Materials

As noted above in the equipment and systems diagram, many equipment units and material handling phases were required to successfully transport dry (bulk) spoil mechanically from the underground work areas to the final points of disposal at various off-site locations. The summary below in Table 8 lists the general arrangements and capacities of specific equipment units incorporated into the rock spoils handling systems.

Treatment for all drill and blast excavation spoil was easily accomplished using mechanical handling equipment. There was no excess water to drain, and all spoils were immediately hauled off-site after very brief on-site storage periods, typically, a few hours only. Final disposal of excavation spoil (without distinction of the origin underground) fell into the following categories: off-site landfills and off-site engineered fills (i.e. commercial building pads and embankments)

- Municipal landfills with controlled access and
  - Material gradation requirements
  - No petroleum residues allowed
- Commercial building pad developments
  - Material gradations requirements
  - Free draining material (specified limits to the "fines" content)

Due to the economics and operational restrictions for "over-the-road" trucking, the maximum haul distances from the site were generally limited to 75 km (40 miles) one-way. Trucking cycle times (per load) as well as the daily allowable start and end times at the site were also a factor in the determination of the most economical approach and locations for the final spoil disposal sites.

None of the excavated spoils received any secondary treatment (or remanufacturing) such as the following before final disposal.

- Oil residue removal (virtually none present on the spoil)
- Removal of any blasting residues and odours (ammonia)

Unfortunately, and due to logistical challenges, none of the excavated spoil was considered useful for any processing and repurposing into alternate end products such as road base, concrete aggregates, or fused into masonry building units. The final material character (i.e. grain size distribution) just prior to off-site disposal, was highly variable and fluctuated depending on the source location(s) and the blast intensity utilized. In general terms, all spoil was <400mm (16") and only and small fraction >150mm (6"). The spoil frequently had an ammonia odour resulting from the use of nitro-glycerine-based blasting materials.

Conclusions

Virtually all of the tunnel spoil material was environmentally disposed of without the use of chemicals or any secondary processing. Overall, the handling, treatment and final disposal of the 72nd Station and Tunnels excavated spoil, approximately 137,720 m3 (180,000 yd3), was considered a great success as considered from environmental, commercial and social considerations. Additionally, there were no residual quantities or impacts remaining related to tunnel spoil materials at the end of the project.

ITEM	TUNNEL ATTRIBUTES	CAVERNS		TUNNELS		TOTALS	
		METRIC	IMPERIAL	METRIC	IMPERIAL	METRIC	IMPERIAL
A	**TUNNEL HAULAGE**						
1	**Scooptrams (LHD)** CAT 1600 scoop CAT 1700 scoop	4.8 m^3 5.7 m^3	6.3 yd^3 7.5 yd^3	4.8 m^3 5.7 m^3	6.3 yd^3 7.5 yd^3		
2	**Front End / Track Loaders** CAT 966 wheel loader CAT 963 track loader CAT 953 track loader	3.5 m^3 2.5 m^3	4.5 yd^3 3.2 yd^3	3.5 m^3 2.5 m^3 1.8 m^3	4.5 yd^3 3.2 yd^3 2.4 yd^3		
3	**Excavators** CAT 321 CAT 314	1.5 m^3 1.1 m^3	2.0 yd^3 1.5 yd^3	1.5 m^3 1.1 m^3	2.0 yd^3 1.5 yd^3		
B	**SHAFT HOISTING**						
1	**Shaft Hoists** North hoist South hoist	19 m^3 19 m^3	25 yd^3 25 yd^3	19 m^3 19 m^3	25 yd^3 25 yd^3		
2	**Surface Spoil Storage** North Muck House hoist South Muck House hoist	230 m^3 230 m^3	300 yd^3 300 yd^3	230 m^3 230 m^3	300 yd^3 300 yd^3		

Table 8: Second Avenue Subway – Tunnel Spoil Handling Equipment
Summary of shaft, tunnel and cavern spoil handling equipment for dry (bulk) hard rock materials excavated using drill and blast methods in all portions of the site.

8.4 OARS TUNNEL PROJECT (USA) – EXCAVATION SPOIL HANDLING AND TREATMENT

The OSIS Augmentation and Relief Sewer Tunnel Project was constructed in Columbus, Ohio, USA between 2012 and 2017. This was a very geotechnically challenging tunnel in its day because of excessive volumes of free-flowing ground water (at 6 bar pressure) hosted in a vuggy (Karstic formation), limestone strata as more fully described below. (See Figures 42, 43 and 44). It was for this reason that unique tunnelling conditions were encountered requiring a hybrid approach to tunnel excavation spoil handling, treatment and disposal. The key data and statistics for the project are listed below and in Table 9.

The OARS Tunnel Project produced 272,660 m³ (359,000 yd³) of excavated tunnel spoil using one hybrid hard rock TBM. The TBM was equipped with both dry (bulk) spoil handling equipment and secondary wet (slurry) handling system design to accommodate approximately 30% of the totals estimated spoil volume excavated under "wet" conditions having high groundwater inflow rates.

OSIS AUGMENTATION AND RELIEF SEWER (OARS) TUNNEL PROJECT – DATA SUMMARY				
TUNNEL LENGTH			**PROJECT DATA**	
East Tunnel	` 6,840m	(23 LF)	Year built Owner Location Contractor	2010 to 2017 City of Columbus, Ohio) Columbus, Ohio, USA Kenny-Obayashi, JV
TUNNEL DIAMETER			**GROUND TREATMENT**	
Excavated Final Lining	7.01m 6.10m	(23’-0”) (20’-0”)	None except for cutter changes Probing and drainage holes	
SPOIL EXCAVATED			**PERMITS**	
Tunnels Shafts (3)	270,850 m³ 45,900 m³	(354,000 yd³) (60,000 yd³)	Ohio-EPA CEQA	Tunnel water inflows limitations Treated water discharge to streams
GROUNDWATER HEADS				
Head Peak inflows	55m >22,700 l/m	(180 feet) (>6,000 gpm)		

All equipment and spoil handling systems were configured for an average tunnel excavation advance rate of 21.4 m/day (70 feet/day) per TBM. Table 9 above summarizes the estimated quantities and rates.

ITEM	TUNNEL ATTRIBUTES	OARS TUNNEL - PLAN		OARS TUNNEL - ACTUAL		TOTALS (OR AVERAGES)	
		METRIC	IMPERIAL	METRIC	IMPERIAL	METRIC	IMPERIAL
A	**TUNNEL PROPERTIES**						
1	Tunnel length	7,110m	23,330 ft	7,110m	23,330 ft		
2	Excavation diameter	7.0m	23 feet	7.0m	23 feet		
3	Excavation linear quantities	38.5 m³/m	15.4 yd³/ft	38.5 m³/m	15.4 yd³/ft		
4	Excavation quantities	273,660 m³	359,000 yd³	273,660 m³	359,000 yd³		
5	Estimated Swell Factor	1.20	1.20	1.20	1.20		
6	Estimated Loose volume	328,400 Lm³	430,800 Lyd³	328,400 Lm³	430,800 Lyd³		
B	**TUNNEL EXCAVATION**						
1	Estimated excavation rates	21.4 m/day	70 ft/day				
2	Actual excavation rates			20 m/day	65 ft/day		
3	Estimated groundwater inflows	2,650 l/min	700 gpm				
4	Actual groundwater inflows			22.7 m³/min	6,000 gpm		

Table 9: OARS Tunnel Project – Dimensions and Quantities
Summary of the tunnel excavation quantities encountered for the OSIS Augmentation Relief Sewer (OARS) tunnel project in Columbus, Ohio.

Figure 42: OARS Tunnel Project – Aerial View and General Arrangement
Plan view of the OARS Tunnel in Columbus, Ohio that generally follows the Scioto River alignment at a depth of approximately 55m (180 feet) below grade. (Courtesy City of Columbus, Ohio).

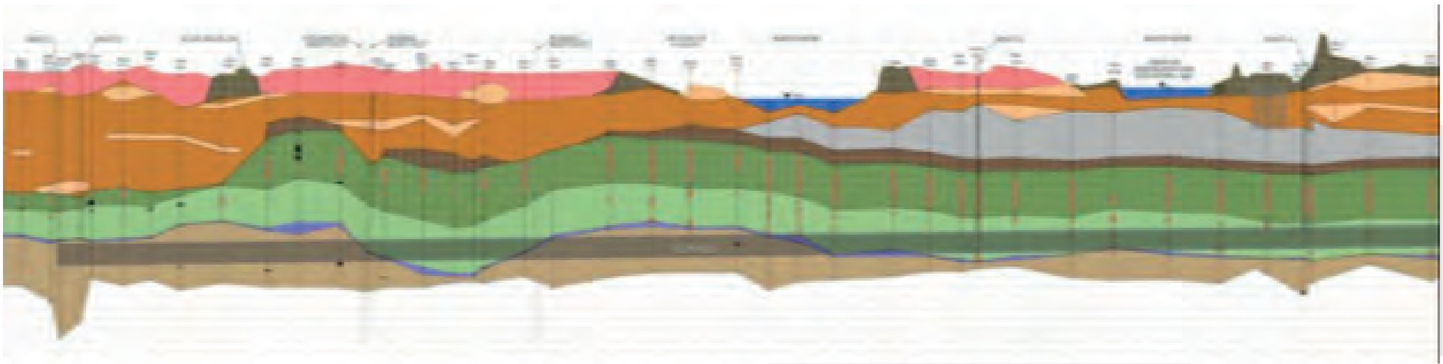


Figure 43: OARS Tunnel Project – Geological Profile View – Lower Reach
Geological profile view of the OARS Tunnel in Columbus, Ohio (lower tunnel reach) at a depth of approximately 55m (180 feet) below grade. (Courtesy City of Columbus, Ohio).

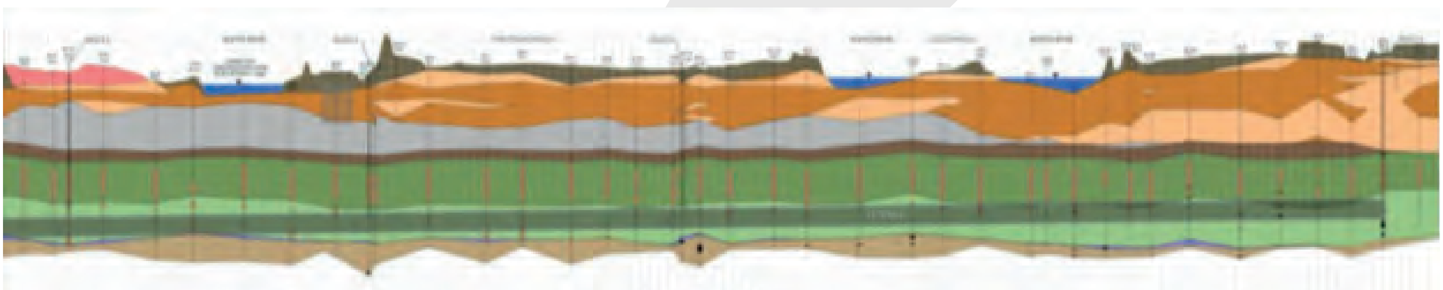


Figure 44: OARS Tunnel Project – Geological Profile View – Upper Reach
Geological profile view of the OARS Tunnel in Columbus, Ohio (upper tunnel reach) at a depth of approximately 55m (180 feet) below grade. (Courtesy City of Columbus, Ohio).

8.4.1 Excavation Spoil Handling and Treatment Systems

The following is an excerpt from the 2015 report titled,". "Challenges in Tunnelling with a Hard Rock Slurry TBM in Columbus, Ohio", 2015, presently at the Rapid Excavating and Tunnelling Conference and describes the site conditions affecting both solid and liquid tunnel spoil materials emanating from this unique tunnel project.

Surface operations were very unique for the project. Approximately 1.6 km (1 mile) south of the main shaft, The Shelly Company (Shelly) operates an open pit limestone quarry and the land between the main shaft and the quarry is owned by the City of Columbus. While karstic limestone and high water flows were anticipated throughout the tunnel reach, the quarry had also encountered these issues over the years and dis¬charges approximately 75,700 m3/day (20 mgd) of water into the nearby Scioto River.

During pre-bid investigations, KOJV and Shelly were able to reach to an agreement that basically swapped water for rock. KOJV would need to install two pipelines to the quarry. One pipeline would tap onto the quarry discharge line and provide all the process water needed for the tunnel project. The second pipeline would carry all tunnel discharge and underflows from the solids separation plant to the quarry where the fines would settle-out and the residual water would then be pumped through Shelly's permitted outfall into the Scioto River. In exchange, Shelly would control all the rock that was to be mined and haul it to the quarry over a new road to be built across the City's land.

Solid Materials – Bulk, Dry Material Handling System

- Tunnelling Boring Machines (one each)
  - Screw auger (need for material conveyance only)
  - Primary conveyor
  - Secondary conveyor
- Tunnel and Portal Haulage (one location)
  - Continuous, extensible tunnel conveyor (TBM to the access shaft)
  - Vertical belt in the shaft
  - Muck hopper and reclaim conveyor
  - Overland conveyor (to on-site stockpile)
- On-Site Mobile Equipment (one fleet)
  - Front-end loaders
  - Over the road haul trucks

Fluidized Materials – Hydraulic Conveyance System

- Tunnelling Boring Machine (one each)
  - Slurry water recirculation system
  - Make-up water supply and measurement system
  - Water + slurry collection points
  - In-line rock crusher mounted within TBM
  - Warman slurry pump (electrically powered)
- Tunnel and Shaft Conveyance (1 location)
  - Tunnel water slurry discharge pipeline
  - Tunnel water slurry recirculation pipeline
  - In-line Warman slurry pumps (electrically powered)
- On-Site Solids Separation Plant and Equipment (1 plant)
  - Screens and cyclones
  large particle (>25mm (1")) extraction at tunnel portal
  - Vertical clarifiers
  small and medium (sand sized) particle extraction
  - Centrifuges
  fine (silt sized) particle extraction
  - Flow controls
  volumetric data loggers for continuous readings

ITEM	TUNNEL ATTRIBUTES	INITIAL – DRY BULK		INITIAL – WET SLURRY		FINAL – WET SLURRY	
		METRIC	IMPERIAL	METRIC	IMPERIAL	METRIC	IMPERIAL
A	TBM COMPONENTS						
1	**Screw Auger** Diameter Length Power	700mm 14m 160 kW	2'-4" 46 feet 215 HP	700mm 14m 160 kW	2'-4" 46 feet 215 HP	700mm 14m 160 kW	2'-4" 46 feet 215 HP
2	**Primary Conveyor** Width Length Power	750mm 20m 45 kW	30 inches 70 ft 60 HP				
3	**In-Line Slurry Pumps** Pipe size Capacity In-Line Discharge Pumps Power			200mm 408 m³/hr 12 each 225 kW	8" 1,800 gpm 12 each 300 HP		
4	**Tunnel Slurry System (final)** Pipe size Capacity In-Line Discharge Pumps Power per Discharge pump					300mm 1,140 m³/hr 8 each 400 kW	12 inches 5,000 gpm 8 each 536 HP

Table 10: OARS Tunnel Project – Tunnel Spoil Handling Systems
Summary of the TBM, tunnel and shaft spoil handling systems for both dry (bulk) and wet (slurry) systems and equipment for the OSIS Augmentation Relief Sewer (OARS) tunnel project in Columbus, Ohio.

8 >> Case Studies and Project Examples – Excavated Spoil Materials

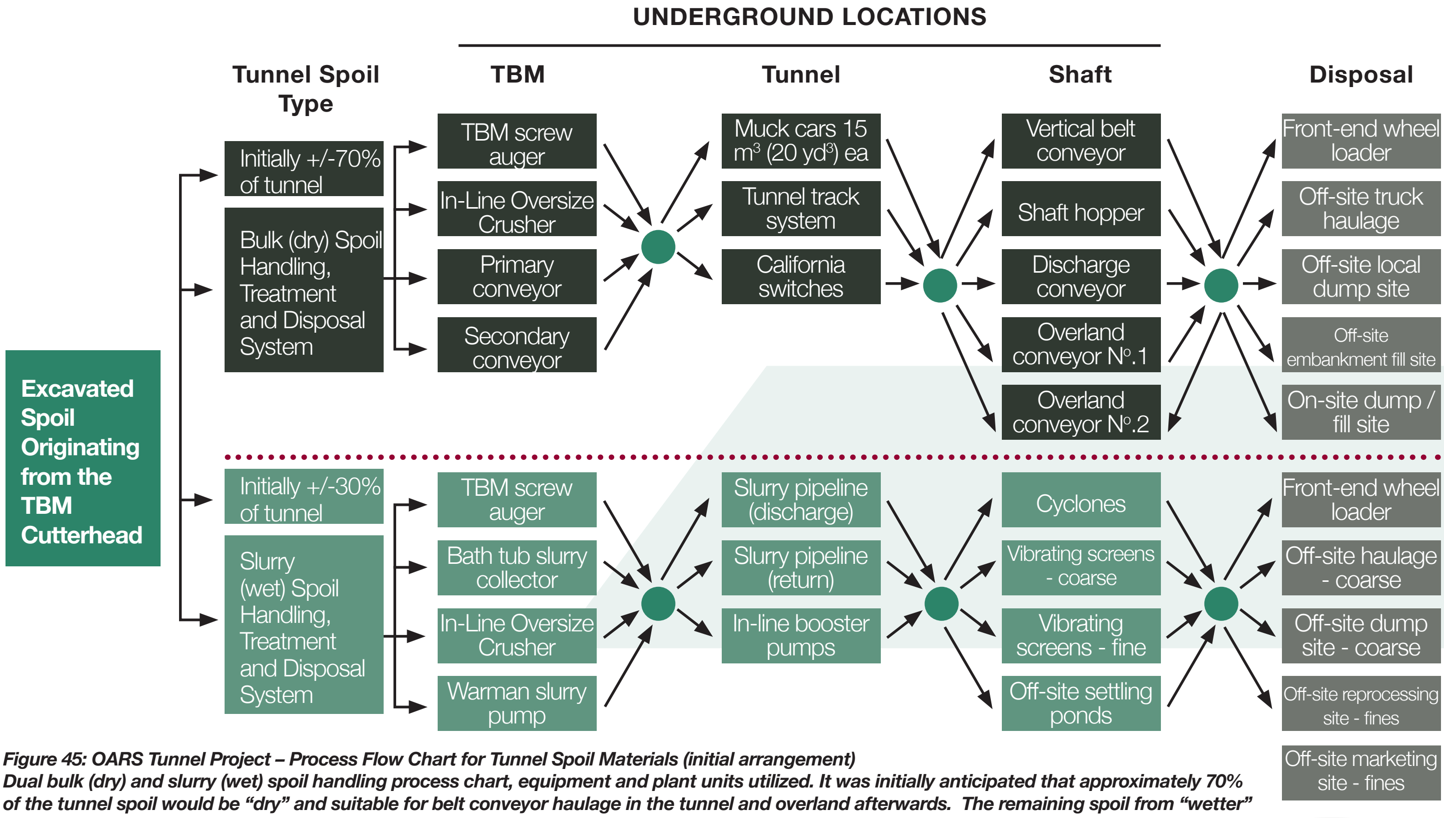


Figure 45: OARS Tunnel Project – Process Flow Chart for Tunnel Spoil Materials (initial arrangement)
Dual bulk (dry) and slurry (wet) spoil handling process chart, equipment and plant units utilized. It was initially anticipated that approximately 70% of the tunnel spoil would be "dry" and suitable for belt conveyor haulage in the tunnel and overland afterwards. The remaining spoil from "wetter" reaches of the tunnel would be too wet (due to excess groundwater inflows) and, therefore, needing a hydraulic system for efficient transport to surface storage areas.

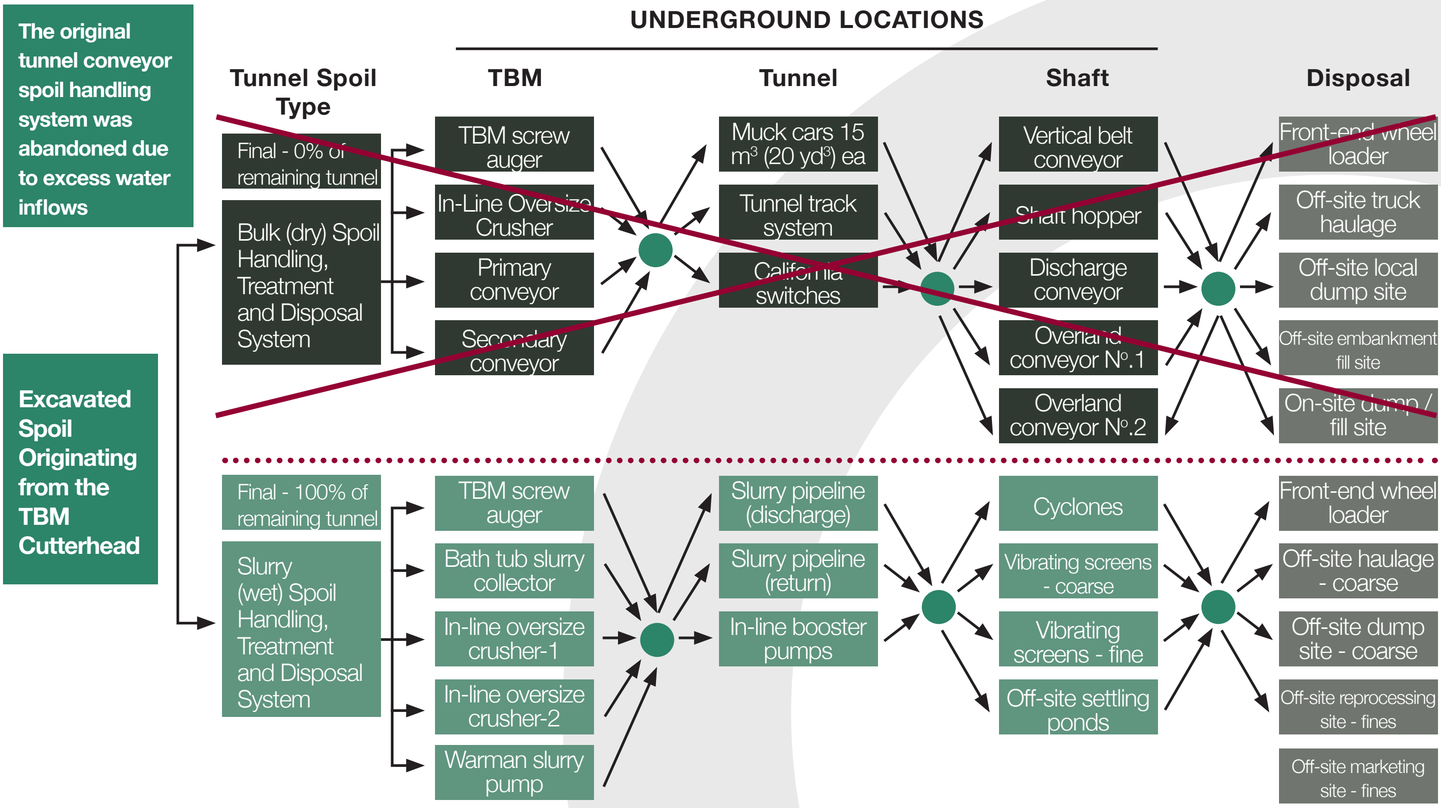


Figure 46: OARS Tunnel Project – Process Flow Chart for Tunnel Spoil Materials (final arrangement)
Slurry (wet) spoil handling process chart, equipment and plant units utilized, since in the presence of excess groundwater inflows, the originally designed dry spoil handling system (tunnel conveyor) was not suitable.

8 >> Case Studies and Project Examples – Excavated Spoil Materials

The process flow charts illustrated below in Figures 45 and 46 summarize the original and modified plant and equipment utilized for handling, treating and final disposal (multiple options) of the rock and spoil material originating from the OARS Tunnel Project. It also summarizes the tunnel wastewater handling and treatment before final disposal into a large nearby settlement pond (existing rock quarry) and local river system.

As noted above in the equipment and system diagram, considerable equipment units and material handling phases were required to successfully transport both dry (bulk) and wet (slurry) tunnel spoil mechanically and hydraulically from the tunnel face to the final point of disposal at the adjacent operating rock quarry. The summary below in Table 10 lists the general arrangements and capacities of specific equipment units incorporated into the unique spoil handling system.

Treatment of the tunnel spoil was only accomplished mechanically and with periods of natural air drying. No chemicals or remixing was performed before final disposal on-site or haul to an off-site location(s). Final disposal of tunnel spoil fell into two distinct categories: on-site engineered fills and off-site landfills and engineered structures.

- On-Site and Adjacent Properties (avoiding extensive trucking)
  - Rock flour extracted from slurry water, dried and sold as a commercial product
- Agricultural lime treatment
- Roadway base lime treatment
  - Infilling of dis-used portions of a nearby rock quarry
- Off-Site (requiring load-out and extensive trucking)
  - Municipal landfills and commercial building foundation pad developments
  - Road base material to meet specifications
  - Concrete aggregate to meet specifications

Due to the nature of the tunnel spoil, whether mechanically or hydraulically transported from the tunnel, was not considered suitable for any of the following secondary uses or manufacturing opportunities.

- Chemically or thermally processed into other end products

While the tunnel spoil (bulk-dry and slurry-wet) had not be treated (or tainted) with any chemicals including bentonite, the consistent fines (>200 mesh) content (passing 0.074mm (0.0029 inch) was very high, largely due to crushing (commutation) as well as multiple handling and screening stages.

The final material character (grain size distribution) just prior to off-site disposal, was generally less than 40mm (1.5 inch) for the majority of the entire excavated tunnel lengths, with a large percentage found to be less than 20mm (0.75 inch).

Conclusions

Virtually all tunnel spoil material was environmentally disposed of without the use of chemicals or any secondary processing. Overall, the handling, treatment and final disposal of 7,010 km (23,000 LF) and 316,750 m^3 (416,000 yd^3) of tunnel spoil material was considered a great success as considered from environmental, commercial and social considerations. Additionally, there were no residual quantities or impacts remaining related to tunnel spoil materials at the end of the project.

8.5 SPARVO TUNNEL (ITALY) – EXCAVATION SPOIL HANDLING AND TREATMENT

The Sparvo Tunnel Project consisted of twin parallel, 2,413m (7,915 LF) long tunnels each with two lanes and a hard shoulder on A1 Motorway in Italy, between Bologna and Florence. Since traffic volumes had grown to approximately 90,000 vehicles/day, an alternative route was needed to augment capacity. The geology in the tunnel route largely comprised clay, sand and limestone and in some sections, high concentrations of methane gas.

Building the tunnel required a 4,500-ton, 130m (425 foot) long EPB shield, "Martina" (Herrenknecht S-574) with 15.615m (51.2 foot) bore diameter which at the time, was the world's biggest EPB shield (Figure 47). Break-through of the first bore occurred after 12 months of continuous excavation at the end of July 2012 attaining peak rates of 22 m/day (72 feet/day). (Figure 48).

8.5.1 Excavation Spoil Handling and Treatment Systems

In the process, up to 4,215 m^3 (5,510 yd^3) of earth was removed on a daily basis (altogether 458,451 m^3 (599,200 yd^3) of excavated material), representing a major challenge for the site management. The soil containing gas required special safety precautions, such as ensuring that the conveyor belts were completely encased, permanent fresh air intake for all sectors as well as continuous monitoring to make sure the casing was tight and of the gas concentration. After breaking-through the first tunnel, the EPB shield was rotated 180° and drove the second tunnel bore located at a 20m (65 feet) spacing from the first bore. The result was peak values of 24 m/day (79 LF /day) and 126 m/week (415 LF/week). The second bore broke-through on 29 Jul 13. Both tunnels were supported with 15m (50 feet) diameter x 2m (6.6 feet) long x 70cm (27.6") thick precast segment tunnel liner rings in a 9+1 configuration and fabricated in a nearby plant.

Geological conditions presented significant demands for both open and closed-face tunnelling methods. In a region characterized by major landslides, the geology comprised predominantly clays, claystone, sandstone and limestone with "floating" ophiolite intrusions found to be up to 300 MPa (43,500 psi) Unconfined Compressive Strength. Added to this, were high concentrations of methane gas.

Mechanised tunnelling using closed-face EPB technology, and a precast concrete segmental lining was promoted as being safer and more assured of steady progress for the twin 2.5 km (1.52 mile) drives of the Sparvo Tunnel.

«Coming to grips with the shear size of the TBM and dealing with the methane gas hazard were the two greatest challenges for the TBM operating crews,» explained Jens Classen. «The TBM is methane explosion protected and it operated at all times in the closed EPB mode to help control the gas.»

A 24m (80 foot) long x 1.6m (5.2 foot) diameter screw conveyor, one of the largest ever used in an EPB machine, is one of the central technical features of the TBM. Another is an independent ventilation system that fed fresh air into the outlet of the screw conveyor to the explosion-proof conveyor belt channel to dilute high concentrations of methane. Please see Figure 49 below.

With the support of local authorities, Toto Construction, the Universities of Bologna and Turin, and Herrenknecht developed a complex safety system which also included a fully enclosed tunnel spoil transfer belt conveyor across the full length of TBM and trailing gear to the continuous tunnel haulage conveyor, a permanent fresh air supply to all areas of the machine, and permanent monitoring of gas concentrations.

Figure 47: Sparvo Tunnel – EPB TBM at Plant
General arrangement view of the EPB TBM at the Herrenknecht plant. (Courtesy of Herrenknecht AG)

Figure 48: Sparvo Tunnel – EPB Tunnel Spoil Conveyor
Tunnel spoil conveyor point of discharge at the surface storage and treatment area.

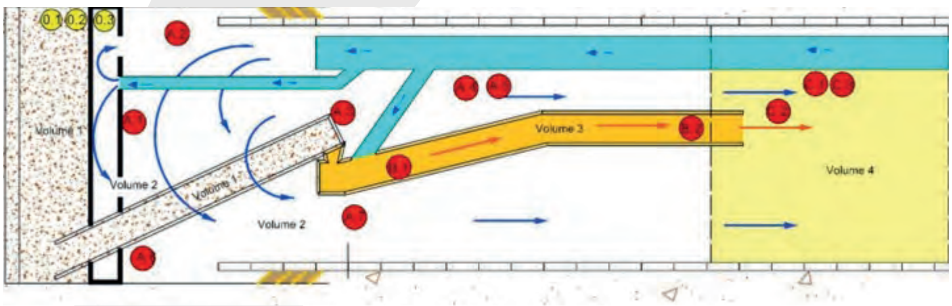


Figure 49: Sparvo Tunnel Project – TBM Profile for Spoil Materials Handling
General arrangements within the TBM for bulk material spoil handling system (including methane gas) and the corresponding tunnel (scavenger) ventilation system and metering points.

Figure 50: Sparvo Tunnel Project – Spoil Treatment (drying and mixing) Site
General arrangements for on-site bulk spoil material handling and storage (including mechanical treatment and chemical mixing) before testing and off-site disposal.

Figure 51: Sparvo Tunnel Project – Spoil Treatment (drying and mixing) Site and Off-Site Haulage
General arrangements for on-site bulk spoil material handling and storage before testing and off-site haulage and disposal.

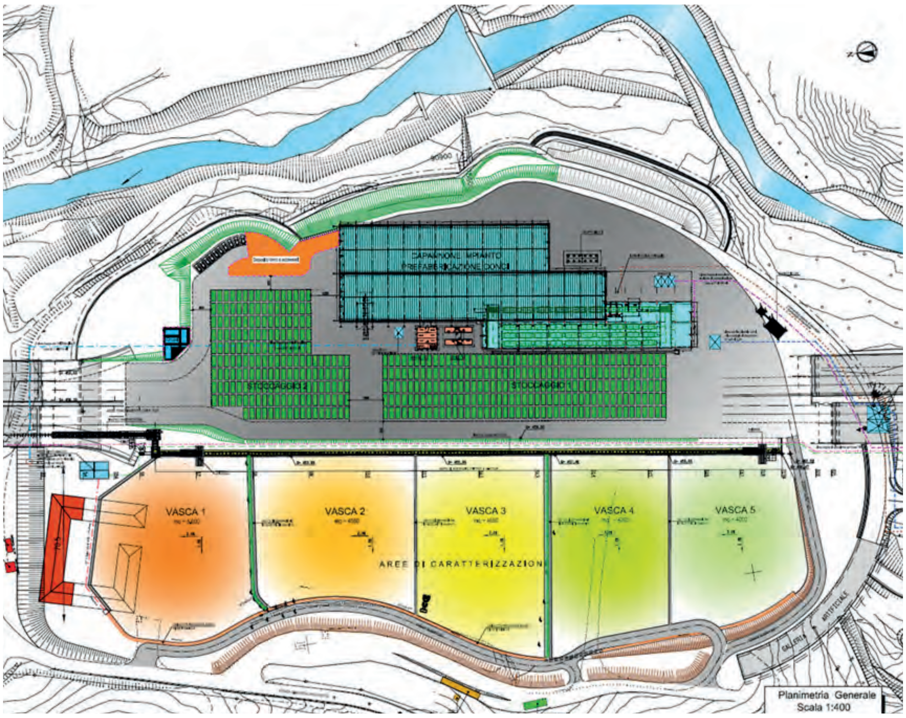


Figure 52: Sparvo Tunnel Project – Plan View Rendering of Precast Plant and Spoil Storage
General arrangements for the on-site precast segmental fabrication plant and bulk spoil material handling and storage (including mechanical treatment and chemical mixing) before testing and off-site disposal.

9 >> Case Studies and Project Examples – Tunnel Wastewater Treatment and Disposal

As noted in Section 3.1, the report authors and contributors developed several Case Studies for the handling, treatment and final disposal options for tunnel spoil materials; including solids, liquids and gases as products of the excavation. The following Case Studies are generally well-known projects that provided good examples of a high standard of care for tunnel wastewater management challenges and solutions from around the globe. These Case Studies should be considered as a small sampling of projects executed in recent years, both completed and still underway.

Normally water on jobsites is treated on-site and discharged to local sewers. Ideally, Contractors should find a way to incorporate the site water back into their tunnelling operation. This could be done to some extent by any of all of the following methods, for example.

- Use as make-up water for water-based slurry handling systems
- Use as mixing water for backfill grout
- Use in the ground conditioning system
- Use in batching concrete
- Tunnel strata recharge systems
- Tunnel equipment cooling systems

In the case where additional (or egregious) residues from tunnelling operations are encountered, these may be result in impacts to existing tunnel spoil handling and treatment facilities and system. While not intended, some essential grouting and tunnel material residues have had a very adverse effect on water treatment plant processes, resulting incompliance discharge flow anomalies. Chemical admixtures (salts) are particularly problematic as are excess quantities of unreacted cement (basic and therefore, low pH levels).

9.1 ARROWHEAD TUNNELS PROJECT – GROUNDWATER HANDLING AND TREATMENT

The Arrowhead Tunnels Project was constructed near San Bernardino, California, USA between 2003 and 2009. This was a very geotechnically challenging tunnel in its day because of highly variable ground conditions as more fully described below. The principle data and statistics for the project are listed below in Tables 11 and 12.

Groundwater conditions as referenced earlier were found to be very difficult to cope with while concurrently maintaining steady excavation advance rates. Two State-of-the-Art, single-shield hybrid TBMs were procured in 2002 that were well equipped with pre-excavation drilling and grouting (and drainage) systems and plant needed to successfully excavate to the tunnel. The groundwater conditions may be generally described as listed below in Table 11.

Over the course of construction, frequent groundwater pressures and flow rate recordings were made. In fact, elaborate flow measurement systems and devices (i.e. Parshall flumes and totalizers) were installed at strategic locations to quantify and record groundwater rates from the tunnels to fulfil US Forest Service permit requirements. US Forest Service groundwater inflow permit restrictions are listed in Tables 11 and 13 for reference.

Figure 53 below is a statistical histogram of measured tunnel water flows over a 40-month period for the Arrowhead West (Waterman) Tunnel. A similar data set and graph was prepared for the Arrowhead East (Strawberry) Tunnel throughout its construction period.

ITEM	GROUNDWATER DATA AND BEHAVIOUR	STRAWBERRY TUNNEL		WATERMAN TUNNEL	
		METRIC	IMPERIAL	METRIC	IMPERIAL
1	Water table above tunnel	275m	900 feet	180m	600 feet
2	Groundwater pressure	27 bar	390 psi	18 bar	260 psi
3	Water quality	Non-Potable (NP)		Non-Potable (NP)	
4	Probe hole flow rates (30m (100ft) long) before initiating pre-excavation grouting	114 l/min Spec req't	30 gpm Spec requ't	114 l/min Spec req't	30 gpm Spec requ't
5	Dissolved gases	None (trace amounts)		None (trace amounts)	
6	CalOSHA Tunnel Classification	***Potentially Gassy***		***Potentially Gassy***	
7	**Groundwater permit regulations**	US Forest Service Permit		US Forest Service Permit	
	Peak allowable flows	**33 l/sec**	**520 gpm**	**37 l/sec**	**580 gpm**
	Peak flow allowable durations	7 days (max)		7 days (max)	

Table 11: Arrowhead Tunnel Project – Groundwater Conditions
Summary of published and as encountered groundwater conditions in the Strawberry and Waterman Tunnels as part of the Arrowhead Tunnel Project.

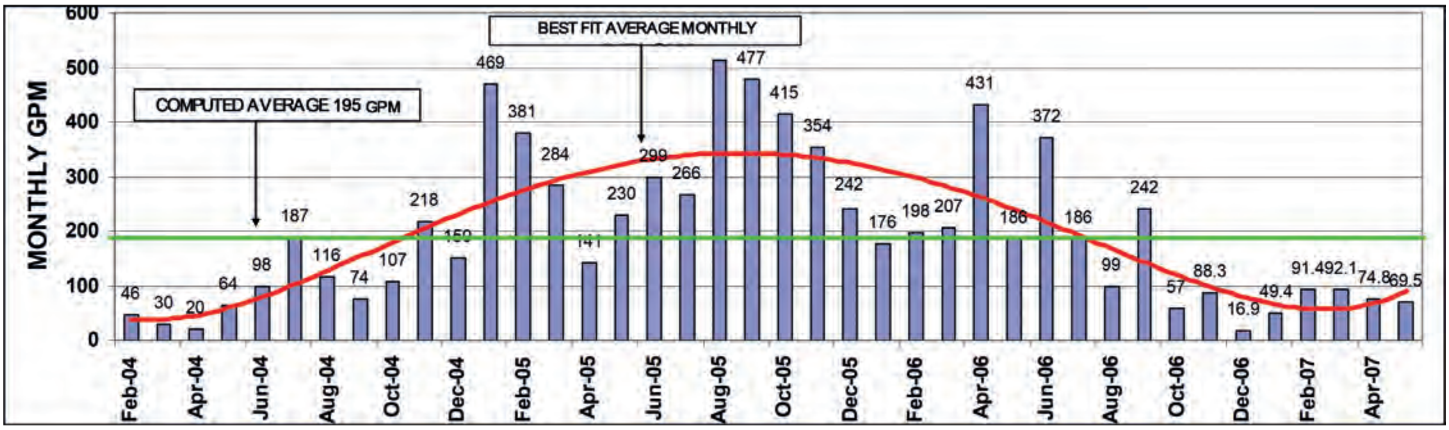


Figure 53: Arrowhead West Tunnel Project – Tunnel Water Inflows
Rolling average daily tunnel water inflows (groundwater) from the Arrowhead West Tunnel (Waterman Tunnel).

9.1.1 Groundwater Conditions and Inflows

The Arrowhead Tunnels were challenged by high groundwater heads within "highly altered" granitic strata. The ground conditions, once disturbed by TBM excavation, were frequently unstable, compounded by pervasive groundwater pressures. The resulting tunnelling conditions were very challenging with occasional face instability. The tunnelling approach, therefore, included extensive pre-excavation drilling and grouting as far as 50m (150 feet) in front of the advancing tunnel face. In fact, the pre-excavation drilling and grouting program included as many as 41 grout holes placed through the face and front shield periphery. In some cases, and due to ground instability (failures) encountered while drilling, downstaging (progressive redrilling and regrouting) programs were needed to fully grout the ground mass satisfactorily as evidenced by outflows from probe hole drilling.

The in-situ ground water conditions may be summarized as listed below in Table 12.

9.1.2 Groundwater Permit Restrictions

The United States Forest Service Construction Permit for tunnel construction restricted groundwater inflows into the tunnel to 33 l/sec (520 gal/min) for the Strawberry Tunnel and 37 l/sec (580 gpm) for the Waterman Tunnel as much as seven days, before more restrictive groundwater inflow measures had to be taken. The permit, therefore, allowed the tunnel excavation to proceed in the presence of 1,900 l/min (500 gal/min) [the permit stipulated groundwater inflows]; to the extent that continuous TBM excavation could be safely and successfully performed under these conditions.

The continuous challenge was to reduce groundwater inflows using extensive pre-excavation grouting methods, validated with measured inflows from probe holes, sufficient to successfully and safely excavate the twin tunnels using highly innovated single-shield hard rock TBMs. Table 13 summarizes the actual groundwater quantities encountered over the course of tunnel construction. As the tunnel advanced, a heavy (330mm thick) precast segmental tunnel liner was installed. The tunnel lining was designed to withstand the ground loads and an external groundwater pressure of up to 27 bar.

9.1.3 Water Treatment Requirements and Discharge Permits

Strict compliance was required under the following permits and water discharge regulations. For the purposes of this Section, water is defined as all water used and encountered in the tunnel during the Contract. The Contract requirements included the following.

- *Waste Discharge Requirements (WDR)/ National Pollutant Discharge Elimination System (NPDES) Permit.*
- *Water Quality Control Plan Santa Ana River Basin 8 (Basin Plan).*
- *All water used and encountered in the tunnel during the Contract will be discharged under Metropolitan's existing WDR Order No. 99-21, NPDES Permit No. CA 8000392, and the associated Monitoring and Reporting Program, the whole document comprising the WDR/NPDES Permit and the Basin Plan, attached and incorporated into the specifications by reference.*

Please note the following under the contract with respect to existing groundwater conditions and requirement treatment before discharge.

- *The groundwater present is at or near the Total Dissolved Solids (TDS) limits allowed for disposal into the surface water creeks. Any treatment or construction activities could increase the TDS beyond the allowable discharge limit. -TheContractorshallnotbeallowedtodischarge water above the TDS limits of 290 ppm. - In the event that the groundwater is above the TDS the water shall be treated to lower the TDS below the discharge limit. - This treatment may require a reverse osmosis unit to meet the requirements.*
- *During the tunnelling operation at Arrowhead East and West Tunnel the Contractor shall be allowed to discharge water from the*

ITEM	TUNNEL ATTRIBUTES	DATA TABLE		GROUND AND GROUNDWATER CONDITIONS		
		METRIC	IMPERIAL	SUBSURFACE	SURFACE	RECHARGE
A	**STRAWBERRY TUNNEL**					
1	Tunnel length	6,840m	22,443'	Yes		
2	Excavation diameter	5.82m	19'-1"	Yes		
3	Groundwater level	275m	900 ft	Yes	Potential depletion	Very slow
4	Groundwater pressure	27 bar	390 psi	Yes		
5	**Groundwater inflow rate (permit)**	**33 l/sec**	**520 gpm**			
6	**Subsurface Conditions** Faults and fractures Shears and brecciated Aquitards Voids Recharge potential			Yes – frequent Yes – frequent Yes – occasional Yes – frequent Yes – frequent		Limited – slow
7	**Surface Conditions** Local water courses Surface water depletion				Yes – seldom Yes – frequent	
B	**WATERMAN TUNNEL**					
1	Tunnel length	6,062m	19,890'	Yes		
2	Excavation diameter	5.82m	19'-1"	Yes		
3	Groundwater level	180m	600 ft	Yes	Potential depletion	Very slow
4	Groundwater pressure	18 bar	260 psi	Yes		
5	**Groundwater inflow rate (permit)**	**37 l/sec**	**580 gpm**			
6	**Subsurface Conditions** Faults and fractures Shears and brecciated Aquitards Voids Recharge potential			Yes – frequent Yes – frequent Yes – occasional Yes – frequent Yes – frequent		Limited – slow
7	**Surface Conditions** Local water courses Surface water depletion				Yes – seldom Yes – frequent	

Table 12: Arrowhead Tunnels Project – Ground and Groundwater Conditions
Overview summary of the surface and underground strata and groundwater conditions as found in and above the location of both Arrowhead tunnels. It is important to note the strict groundwater inflow restrictions imposed by the US Forest Service permits (allowing the tunnels to be constructed).

ITEM	TUNNEL INFLOW RATES AND PERIODS	STRAWBERRY TUNNEL		WATERMAN TUNNEL	
		METRIC	IMPERIAL	METRIC	IMPERIAL
1	**Permitted flow (peak) [max 7 days]**	**33 l/sec**	**520 gpm**	**37 l/sec**	**580 gpm**
2	**Estimated Continuous flows:** Per hour (all underground sources) Per day (24 hours) Per week (24/7) Per month (30 days)	118 m³ 2,834 m³ 19,840 m³ 595,230 m³	31,200 gal 748,800 gal 5,241,600 gal 157 million gal	145 m³ 3,161 m³ 22,130 m³ 663,810 m³	34,800 gal 835,200 gal 5,846,400 gal 175 million gal
3	Project Duration (As-Built schedule)	44 months		47 months	
4	**Total Estimated Tunnel Inflow Volume**	26.2 million cubic metres	6,908 billion gallons	31.2 million cubic metres	8,242 billion gallons

Table 13: Arrowhead Tunnels Project – Groundwater Inflow Rates and Volumes
Summary of the groundwater inflow rates and volumes into the Arrowhead tunnels. These inflow rates and overall volumes had to remain in strict compliance with the permit restrictions imposed by the US Forest Service.

tunnelling operations into East Twin Creek in a quantity not to exceed 4.0 MGD. - No other discharge sites are approved for discharge of tunnel operation water. - In the event that the Contractor's construction operations produce more than 4.0 MGD, the Contractor shall dispose of the excess water off-site or provide temporary storage to discharge the water when the daily output is below 4.0 MGD.

- *After tunnel excavation has been completed at both the Arrowhead East and West tunnels, the Contractor shall be allowed to discharge a maximum of 1.0 MGD to East Twin Creek from construction operations at Arrowhead West tunnel, and 3.0 MGD to City Creek from construction operations at Arrowhead East. - In the event that the Contractor's construction operations produce more than allowed volumes the Contractor shall dispose of the excess water off-site or provide temporary storage to discharge the water when the daily output is below the allowed volume.*
- *Construction activities could increase the TDS beyond the allowable discharge limit of 290 mg/l. - The Contractor shall not be allowed to discharge water above the TDS limits of 290 mg/l regardless of what the NPDES permit allows. - In the event that the groundwater is above the allowable TDS limits the water shall be treated to lower the TDS below 290 mg/l.*

9.1.4 Water Treatment and Discharge Submittal Requirements

As a condition of discharge under the general WDR/NPDES Permit, the Contractor was required to prepare various submittals to demonstrate compliance. For each proposed discharge, the Contractor was required to submit an application to the Engineer. The application had to be submitted at least 90 days prior to the start of the discharge. It had to be stamped by a civil engineer registered in the State of California and include:

- *Report describing the treatment system and demonstrating compliance with the WDR/NPDES Permit*
- *Operation and Maintenance (O & M) Manual*
- *Drawings showing the facilities and discharge location*
- *Average and peak flow rates*
- *Monitoring plan and Quality Assurance (QA) plan. The QA plan shall describe the test methods, accuracy, detection limits, blank duplicate and spiked sampling and all procedures and practices (including the use of chain-of-custody forms)*

In addition to above submissions, the following reports were required on the frequencies noted.

- *Annual report summarizing QA activities for the previous year due January 20th*
- *Monthly monitoring reports*

The Contract specifications were particularly expectant in the manner, scope and reporting frequency related to water discharge testing records. Please refer to the Appendices in Section 15 for additional information related to the water discharge quality measurement and reporting requirements specified for the Arrowhead Tunnels Project.

9.1.5 Water Discharge Specifications

Based on the Contract specifications for the Arrowhead Tunnels Project, the discharge of construction water could not contain constituents in excess of the limits listed below in Table 14.

The discharge could not result in acute toxicity in ambient receiving waters. Discharges were deemed acutely toxic when:

- *The toxicity of 100% effluent (as required in the Monitoring and Reporting Program No. 99-21) results in less than 70 percent survival rate of the test organisms in any single test.*

ITEM	CONSTITUENT	ABB.	MAXIMUM CONCENTRATION OR CONDITION	
			METRIC	IMPERIAL
1	Total Dissolved Solids	TDS	290 ppm	
2	Total Suspended Solids	TSS	50 mg/l	0.006 oz/gal
3	Sulfides		0.4 mg/l	0.00006 oz/gal
4	Total Petroleum Hydrocarbon	TPH	0.1 mg/l	0.00001 oz/gal
5	Oil and grease	POL	10 mg/l	0.0013 oz/gal
6	Settleable solids		0.1 mg/l	0.00001 oz/gal
7	pH levels		>6.5 and <8.5	
8	Visible oil or grease		None	

Table 14: Arrowhead Tunnels Project – Water Discharge Specification
Allowable properties of discharge water (after treatment) from the site in accordance with applicable permits and regulatory requirements.

9.1.6 Groundwater Inflows and Treatment Processes

Pre-excavation drilling and grouting occupied more than half of the schedule time dedicated to tunnelling operations and was considered essential for successful TBM advance under the anticipated ground conditions. The residual products of the excavation process included the following.

- Tunnel spoil material; granitic, gneissic and marbles
- Groundwater
- Residues from:
  - Cementitious grouts
  - Chemical grouts
  - Grout admixtures and accelerants (i.e. sodium chloride (NaCl) used with sodium silicate grout)
  - Petroleum, oils and lubricants (POLs)

Acid was used to bring the water down to the correct pH. Site water is typically "basic" on the pH scale from the alkalis present in cement. Coagulants and/or flocculants were also used to remove the suspended solids down to a level acceptable to the local water authority. The measure of this is "turbidity".

The mixture of groundwater inflows from the tunnel had to be treated in a manner to be successfully (and continuously) discharged into a local natural water course while meeting all water quality requirements. The acceptable discharge water quality could therefore not exceed.

- Total dissolved solids (TDS) limits
- Total suspended solids (TSS) limits

Third-Party water quality tests on treated water discharges were performed monthly (or more frequently) in accordance with the prevailing permits and local regulations governing discharges into local water courses. Please refer to Figures 54 and 55 below that illustrate the substantial investment in plant and equipment needed to treat all tunnel water to within specified tolerances and characteristics before allowable discharge into nearby water courses.

Figure 54: Arrowhead Tunnels – Water Treatment
Aerial view of one of the larger water treatment plants used to service the tunnels concurrently.

Figure 55: Arrowhead Tunnels – Water Treatment
Aerial view of one of the smaller water treatment plants used to service the tunnels concurrently.

9 >> Case Studies and Project Examples – Tunnel Wastewater Treatment and Disposal

The water treatment facilities were designed to service two tunnels excavated concurrently. Capacity was, therefore, 3,785 l/min (1,000 gal/min) with storage for occasional peak (flush) flows for short periods of time. The primary and secondary water treatment facilities included the following, combined plant for both tunnels;

- Flow-through oil / water separation basins
- Sedimentation ponds with flocculant treatment
- Flow-through sand filters for secondary sediment extraction
- CO^2 injection for pH adjustment to processed water
- Acid injection system for pH adjustments to processed water
- Reverse Osmosis (RO) processing

All of the above listed systems, equipment and devices were used in a coordinated manner to;

- Remove lubricants (initially)
- Reduce large and fine sediment particles
- Adjust pH levels to within allowable range
- Improve discharge water quality as measured by TDS and TSS levels and other contaminants

All tunnel water (including groundwater inflows) were initially conveyed and processed with "fine" tunnel spoil (water slurry conveyance system) commencing at the TBM cutterhead. The tunnel water conveyance system included the following equipment units operated on a continuous bass as the TBMs advanced through variable geologies and water-bearing strata.

- Screens and cyclones
  large particle extraction at the tunnel portal
- Vertical clarifiers
  small and medium (sand sized) particle extraction
- Centrifuges
  fine (silt sized) particle extraction

Water flow rates discharging from the initial tunnel spoil/water separation plant were measured through a Parshall Flume and totalized flow measurement devices equipped with a data logger. This was needed to generate reliable water flow measurements for reporting requirements to remain in compliance with the US Forest Service Construction and Groundwater Inflow Permit requirements. Detailed records were maintained to reliably determine the following.

- Water volumes within the tunnel spoil / water system needed to maintain particle suspension and flow efficiencies
- Water "imported" into the tunnel for construction needs (variable)
- Groundwater inflows (calculated) from all measured input and the Parshall Flume placed in the combined discharge flow stream

Daily and monthly reports were prepared and submitted to the project Owner and environmental regulatory agencies as well as the US Forest Service to record all flows from tunnelling operations with particular attention to the residual groundwater flows (vis-à-vis permit restrictions and compliance). Figure 56 illustrates the process flow diagram for the combined water treatment plant, designed and sized to service both tunnels concurrently throughout the excavation period.

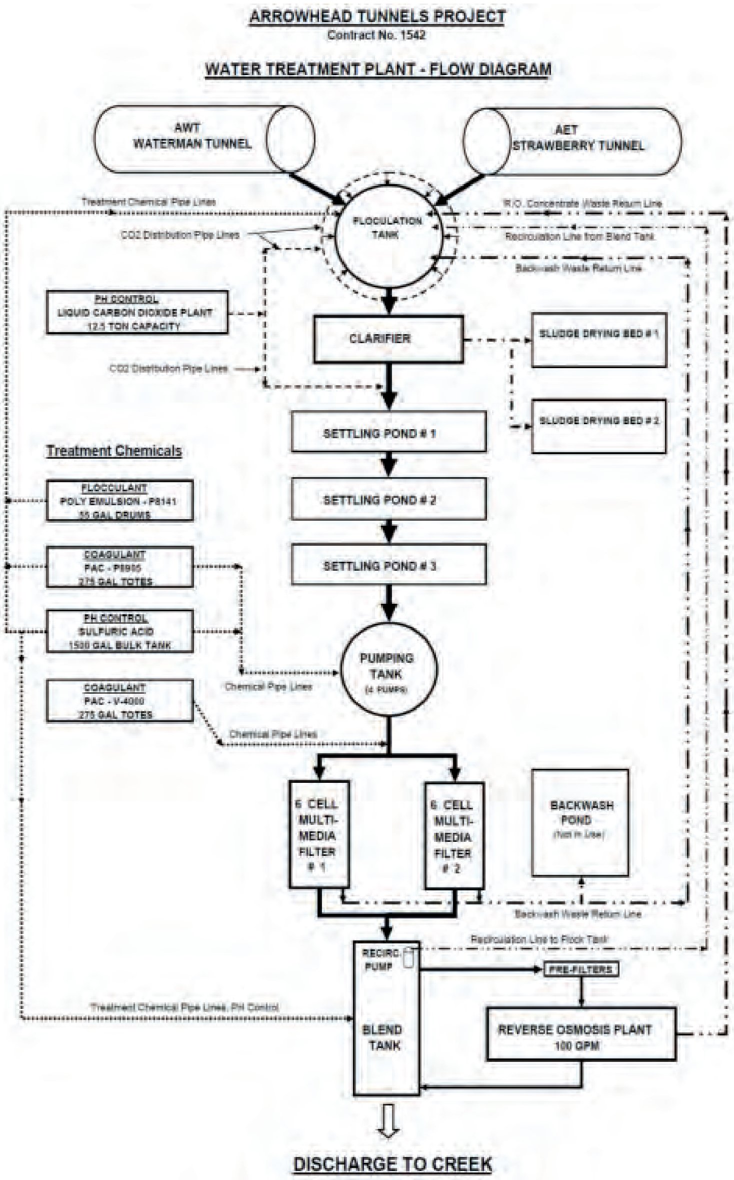


Figure 56: Arrowhead Tunnels Project – Tunnel Water Inflows and Treatment Process Flow Chart
Detailed process flow chart describing tunnel water (all sources) inflows to the water treatment plant; the equipment, facilities and chemical injections needed.

9 >> Case Studies and Project Examples – Tunnel Wastewater Treatment and Disposal

9.1.7 Pre-Excavation Drilling and Grouting Program for Groundwater Control

The extensive pre-excavation drilling and grouting program was deemed successful in controlling groundwater inflows and, therefore, improving ground stability needed for successful and safe mechanized tunnelling operations. Groundwater inflows and pressures were also reduced by virtue of a significant change to ground permeability. The reduction in high pressure groundwater inflows consequently benefited the downstream wastewater treatment plant. Overall, the pre-discharge treatment plant as more fully described above, was successful. The initial investment, maintenance and operation costs were substantial for all potions of the water treatment plant.

Considerable discussion and technical documentation related to the extensive pre-excavation drilling and grouting program intended for ground support and groundwater control are listed below as well as in Section 14 – References and Additional Reading Materials.

- "Piercing The Mountain and Overcoming Difficult Ground And Water Conditions With Two Hybrid Hard Rock TBMs", 2007, Rapid Excavating and Tunnelling Conference Proceedings.
- "Pre-Excavation Drilling and Grouting for Water Control and Ground Improvement in Highly Variable Ground Conditions at the Arrowhead Tunnels Project", 2008, North American Tunnelling Conference Proceedings.

9.2 SECOND AVENUE SUBWAY – GROUNDWATER HANDLING AND TREATMENT

The Second Avenue Subway Project was constructed in New York City between 2010 and 2013. The project consisted of several separate station and tunnel contracts as listed below and benefited from favourable hard rock conditions at shallow depths.

- 63rd Street Station
- 72nd Street Station and Tunnels Project
- 86th Street Station
- 96th Street Station
- Running tunnels Contract (96th to 63rd Streets)

9.2.1 Groundwater Inflows and Treatment Processes

Groundwater issues were virtually non-existent due to the granitic / schistose nature of the ground in all areas of subsurface excavation in New York City's Upper East Side. Just the same, the project had regulations affecting the discharge of all tunnel water (including trace levels of contaminants within the groundwater). The following describes the water handling and treatment of a near constant flow of tunnel water originating from all underground work areas. Please see Figures 57 and 58 below that illustrate the on-site water treatment plant.

- Collection
  - Tunnel drainage courses and sumps
  - Cavern drainage courses and sumps
- Treatment
  - Underground sediment ponds and oil-water separators
  - Surface treatment plant; 815 l/min (215 gpm) capacity
- Discharge
  - Disposal into the NYC DEP sewer system (located under Second Avenue)

Figure 57:* *Second Avenue Subway – On-Site WTP
Aerial view of the compact wastewater treatment plant located in Second Avenue; operated 24/7.

Figure 58:* *Second Avenue Subway – On-Site WTP
Interior view of the compact wastewater treatment plant located in Second Avenue; operated 24/7.

9.3 OARS TUNNEL – GROUNDWATER HANDLING AND TREATMENT

The OSIS Augmentation and Relief Sewer (OARS) tunnel project was challenged by high groundwater heads and excess inflow rates. Although estimated to be 85 to 90% good quality dolomite and limestone rock (Figures 59 and 60) having good to fair to excellent RQD values, there are three anticipated bedded planes of Columbus Limestone Basal Conglomerate as well as three possible faults and a number of voids, karsts and solution features. In these anomalies, hydrostatic water pressures of up to 5.2 bar and more were anticipated.

The ground conditions were stable but frequently impacted by steady high volume groundwater flows and pressures. The tunnelling approach, therefore, included a hybrid TBM (similar to the Arrowhead Tunnel TBMs) where spoil would either pass through a screw conveyor extending from the invert of the excavation chamber through the pressure bulkhead to pass through two gates and onto a continuous tunnel conveyor to the surface or, extracted as a water-based slurry and pumped to a surface solids separation plant. When operating in the semi-closed mode through the screw conveyor, a tub under the discharge gates captured water and fines that was transported to the surface also in a slurry circulation system.

The in-situ ground water conditions have been summarized as listed below in Table 15.

9.3.1 Groundwater Conditions and Inflows

An excerpt from a 2016 RETC report titled; "Designing and Building CSO Tunnels in Midwestern Geology - A Critical Review and Study of Project Implementation and Construction Methods" characterized the ground and groundwater conditions for the OARS tunnel as follows.

"Extensive karstic limestone in Columbus called for outside-the-box thinking on how to handle ground water flows of 1,100 m^3/hr (4,840 gpm) at pressures of 3.8 bar during cutterhead interventions to inspect and change disk cutters. Typical cut-off grout methods through the mid-shield and cutterhead of the Herrenknecht SPBM did not work. Reverse flow cut-off grouting, as was developed and used in two initial shafts prior to tunnelling, was used and adjusted accordingly by changing methods, equipment and grout mixes as the tunnel was progressed."

9.3.2 Groundwater Permit Restrictions

Several groundwater control provisions were required within the Contract provisions. The tunnel excavation approach had to accommodate considerable water inflows or introduce suitable groundwater inflow control measures.

- The ground conditions were such that widespread inter-connected vuggy strata contained enormous quantities of groundwater with some contaminated from prior unregulated industrial waste disposal.
- The ground could not be successfully (or economically) grouted for cut-off from inflows
- The local area drawdown curve was very flat with immediate and infinite recharge characteristics
- Local area dewatering to reduce pressures and inflow to the TBM were deemed impractical due to the volumes, time and limited effects from well fields proposed for the tunnel alignment.

Figure 59: OARS Tunnel – Segmentally Lined
View of the completed segmentally lined tunnels at Shaft 6 (upstream tunnel terminus). (Courtesy of Kenny Construction)

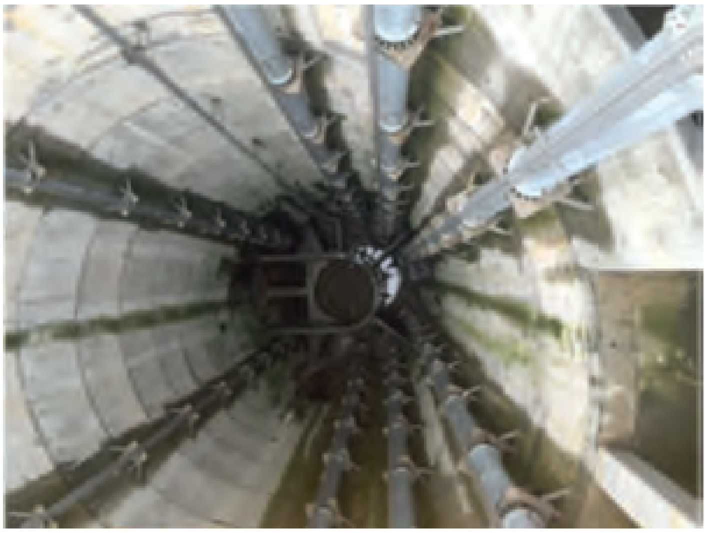


Figure 60: OARS Tunnel – Access and Pump Shaft
Interior view of the access and pump shaft used for the TBM launch and tunnel spoil handling operations. (Courtesy of Kenny Construction)

ITEM	TUNNEL ATTRIBUTES	DATA TABLE		GROUND AND GROUNDWATER CONDITIONS		
		METRIC	IMPERIAL	SUBSURFACE	SURFACE	RECHARGE
A	OARS TUNNEL PROJECT					
1	Tunnel length	7,110m	23,330'	Yes		
2	Excavation diameter	7.0m	23'-0"	Yes		
3	Groundwater level	55m	180'	Yes	Potential depletion	Very slow
4	Groundwater pressure	5.7 bar	83 psi	Yes		
5	**Groundwater flow rate (Contract)**		**700 gpm**			
6	**Subsurface Conditions** Faults and fractures Shears and brecciated Solution features Voids and Karst formations Recharge potential			Yes – frequent Yes – possible Yes – occasional Yes – frequent Yes – pervasive		Yes
7	**Surface Conditions** Local water courses Surface water depletion (floods)					

Table 15: OARS Tunnel Project – Ground and Groundwater Conditions
Overview summary of the surface and underground strata and groundwater conditions as found in and above the location of the OARS Tunnel. It is important to note the strict groundwater inflow restrictions imposed by the Ohio EPA (regulatory agency) in order to preserve local area groundwater levels.

The Contract specifications indicated that many local businesses and residences had shallow wells for water supplies. Existing groundwater levels, therefore, had to be maintained. Although not specifically addressed, any local subsurface groundwater contamination had to remain in-situ (undisturbed) due to tunnelling and groundwater control measures. Therefore, no mitigation or removal of known contaminations was allowed (or desirable).

9.3.3 Groundwater Control Measures

Due to excessive naturally occurring groundwater volumes and pressures (6 bar pressure at tunnel depth) as well as the highly permeable ground conditions, local area grouting around the tunnel was not attempted. Instead, only selective «water control grouting» methods were undertaken immediately around the TBM (only) as and when needed for periodic cutterhead inspections and disk cutter replacements. The existing groundwater conditions remained largely undisturbed in their natural state.

The actual groundwater control measures surrounding the TBM are not the subject of this paper. Nonetheless, they were successful in temporarily controlling 22,700 l/min (6,000 gpm) inflows from the tunnel face and surrounding the TBM shield. Additional groundwater flows migrated to the cutterhead are from around the precast segmental tunnel lining (i.e. shunt flows). See Section 15 – Reference and Additional Reading Materials for additional information.

9.3.4 Groundwater Inflows and Treatment

A pre-excavation drilling and grouting program was not attempted to aid TBM advance on this project. This was due to the vast and inter-connected vuggy strata (Karst formations and solution cavities) where any successful water control grouting program would require weeks (or months) of continuous injection of large (and unpredictable) quantities of grout material(s) for every intervention stage. Thus, pre-excavation grouting was not deemed to be technically or economically advisable, hence a highly localized "water control" grouting solely around the TBM was successfully developed and utilized as and when needed. Water Control grouting program required controlled quantities of cementitious grout applied at pressures and volumes form with selected injection ports surrounding the TBM cutterhead and shield body. No drilling was required. Please refer to the report titled, "Challenges in Tunnelling with a Hard Rock Slurry TBM in Columbus, Ohio", presented at the Rapid Excavating and Tunnelling Conference in 2015 that provides details related to a "reverse flow grouting" technique successfully implemented on the project.

The mixture of groundwater inflows from the tunnel had to be treated in a manner to be successfully (and continuously) discharged into a local natural water course while meeting all water quality requirements. The acceptable discharge water, therefore, could not exceed the following limiting parameters as outlined in the Contract.

- Total Dissolved Solids (TDS) limits
- Total Suspended Solids (TSS) limits

Third-Party water quality tests on treated water discharges were performed monthly (or more frequently) in accordance with the prevailing permits and local regulations governing discharges into local water courses.

Water treatment facilities, once adopted for full hydraulic spoil conveyance in the tunnel, were designed to handle peak flows to as much as 22,700 l/min (6,000 gpm). In that this was a substantial undertaking, dedicated facilities and linear plant were needed and operated continuously.

- Facilities - Surface
  - Solids separation plant
  - Tunnel water pumping system
  - Tunnel water sedimentation ponds
- Linear plant - Tunnel
  - 300mm (12») diameter supply and return pipelines
  - In-line slurry pumps
  - Flow control and measurement devices (i.e. slide plat valves)
- Linear Plant - Surface
  - Welded HDPE 600mm (24») diameter pipelines, 1,000 m (3,300 feet) connecting the tunnel work site to a nearby commercial limestone quarry and sedimentation ponds
  - Flow control and measurement devices

The primary water supply for the tunnel hydraulic spoil conveyance system was groundwater originating from the tunnel face. Due to the large and continuous quantities encountered, no additional (make-up) water was introduced into the system for continuous and uninterrupted spoil conveyance from the TBM to the surface solids separation plant.

9.4 ACID DRAINAGE ROCK AND METAL LEACHATE

Acid Mine Drainage or Acid Metalliferous Drainage (AMD), or Acid Rock Drainage (ARD) is the outflow of acidic water from metal mines or coal mines.

Acid Rock Drainage occurs naturally within some environments as part of the rock weathering process but is exacerbated by large-scale earth disturbances characteristic of mining and other large construction activities, usually within rocks containing an abundance of sulphide minerals. Areas where the earth has been disturbed (e.g. construction sites, subdivisions, and transportation corridors) may create acid rock drainage. In many localities, the liquid that drains from coal stocks, coal handling facilities, coal washeries, and coal waste tips can be highly acidic, and in such cases, it is treated as acid rock drainage. This liquid often contains toxic metals, such as copper or iron. These, combined with reduced pH, have a detrimental impact on the stream's aquatic environments.

The same type of chemical reactions and processes may occur through the disturbance of acid sulphate soils formed under coastal or estuarine conditions after the last major sea level rise, and constitutes a similar environmental hazard. [Wikipedia].

9.4.1 Occurrence and Conditions

The introduction of water is the initial step in most acid rock drainage situations. After being exposed to air and water, oxidation of metal sulphides (often pyrite, which is iron-sulphide) within the surrounding rock and overburden generates acidity. Colonies of bacteria and archaea greatly accelerate the decomposition of metal ions, although the reactions also occur in an abiotic environment. These microbes, called extremophiles for their ability to survive in harsh conditions, occur naturally in the rock, but limited water and oxygen supplies usually keep their numbers low. Special extremophiles known as Acidophiles especially favour the low pH levels of abandoned mines. In particular, Acidithiobacillus ferro-oxidans is a key contributor to pyrite oxidation.

Metal mines may generate highly acidic discharges where the ore is a sulphide mineral or is associated with pyrite. In these cases the predominant metal ion may not be iron but rather zinc, copper, or nickel. The most commonly mined ore of copper, chalcopyrite, is itself a copper-iron-sulphide and occurs with a range of other sulphides. Thus, copper mines are often major culprits of acid mine drainage.

In addition, acidic drainage may be generated for decades or centuries after it is first detected. For this reason, acid mine drainage is considered a serious long-term environmental problem associated with mining.

9.4.2 Case Study 1: Britannia Mine, British Columbia, Canada

Prior to the reclamation work undertaken by the University of British Columbia and the Provincial Government, the clear and transparent water in Britannia Creek suggested a pristine environment, however, the clear water was actually an indication that no living creatures could survive in it. The water could not be consumed by humans either.

Although mining at Britannia Creek (Figure 61) stopped in 1974, run-off and rainwater that flowed through the mine's abandoned tunnels combined with oxygen and the high sulphide content of the waste rock to create a condition called Acid Rock Drainage (ARD). As a result of ARD, Britannia Creek became severely polluted. And, for close to a century prior to December 2001, polluted run-off was being deposited directly into Howe Sound via Jane Creek and Britannia Creek; as much as 450 kg (close to 1,000 lbs) of copper was entering Howe Sound daily. (Figure 62)

A 2 km (1.2 mile) strip of coastal waters along Britannia Beach was seriously polluted, affecting 4.5 million juvenile chum salmon from the Squamish Estuary. A Canadian federal fisheries report revealed that spring salmon held in cages off Britannia Creek died in less than 48 hours because of the toxic metals in the water, whereas fish held off Porteau Cove located several kilometres to the south, had a 100% survival rate.

In the summer of 2001, the Province of British Columbia formally announced that a large-scale treatment plant would be built to neutralize the run-off coming from the old mine site. Although the treatment plant did not become fully operational until 2006, its construction marked a pivotal turning point for Howe Sound and the community of Britannia Beach. The plant treats an average of 4.2 billion litres (1.1 billion gallons) of run-off annually, removing an average of 226,000 kg (500,000 lbs) of ***heavy metal contaminants.***

Figure 61: Britannia Mine Ore Processing Building
Britannia Mine ore processing facility; before conveying concentrate to marine loadout.

Figure 62: Britannia Mine Marine Facilities
Remnants of the Britannia Mine dock and marine loadout facility; (decommissioned in 1974).

9.4.3 Case Study 2: Assessment of ARD/ML for a Rock Tunnel, British Columbia, Canada

The investigation and assessment for a new 5 km hard rock TBM tunnel within 100 km of Vancouver was undertaken in a staged approach. The assessments and investigations are set-out below, as an example of the approach to assessing ARD / ML in a rock mass.

The ground above the tunnel was comprehensively geologically and geotechnically mapped. This was facilitated by excellent surface exposures of the granitic rock above the alignment. During the mapping it was noted that that iron-stained rock was present alongside mineralization including pyrite. Initial samples of rock were collected and underwent acid-based accounting testing to assess the potential for acid generating rock. Further investigations of the rock were carried-out using intrusive boreholes to recover HQ and NQ sized rock cores. Following comprehensive logging of the cores to the ISRM standards, samples were collected at regular and set intervals along the core, as well as at selective locations. The intent of this sampling was to undertake both biased and unbiased sampling and testing.

The results of the acid-based accounting testing from the rock cores, in combination with the geological mapping, was that there was a localized section of tunnel where Potentially Acid Generating (PAG), rock might be found. Additional testing was undertaken of the rock that was considered to be Potentially Acid Generating in that four key samples were taken based on the following rationale: One sample from rock that was certain to be acid generating, one sample that was considered to be borderline, a mixed sample, and a further acidic sample. These samples were sent for testing in humidity cells whereby the sample is crushed to a sand size and water percolated over the sample. Weekly analysis of metals, pH, and other chemical compounds was undertaken. The samples were kept in the humidity cells for over 120 weeks.

A geochemical modelling analysis of the results was undertaken in order to interpret the results from the humidity cells and rationalize the results to rock which might be derived from the conveyor following excavation by a TBM. In other words, draw key conclusions on how the rock on-site would behave in terms of acidic water generation and metal leaching (ARD/ML) out of a stockpile. The key conclusion was that acidic water would be generated from between 20 to 50 weeks in a stockpile of rock (i.e. tunnel spoil material) left uncovered, and if rainfall precipitation was allowed to percolate through the stockpile.

The testing allowed a strategy for ARD/ML rock management that was incorporated into the project's specifications, Geotechnical Baseline Report (GBR) and other tender documentation. In summary the strategy was that all rock from a certain section of the tunnel would be stockpiled within a geomembrane lined cell, from which water in the stockpile drained to a draw point (for collection, treatment and thence disposal). The stockpile was covered routinely to prevent rainfall from percolating through it and, therefore, retard the on-set of acidic conditions. Powdered agricultural lime was used to further suppress the chemical (and micro-bacterial) reactions that form acid. Following tunnelling, the rock tunnel spoil from the stockpile was transferred back into the tunnel as backfill. This backfill will be permanently submerged by water in the tunnel and, therefore, impede and prevent the ARD/ML reactions in the long-term.

In summary, through the proactive engagement of specialists, the ARD/ML potential on the project was characterized, investigated, and assessed. The management strategy developed included both technical and contractual aspects. On any such project, the management of ARD/ML issues should consider both the short and long-term mitigation strategy.

9.5 LOS ANGELES METRO TUNNELS – METHANE AND HYDROGEN SULPHIDE GAS OCCURRENCES

Several very notable tunnel projects have been constructed in the Los Angeles, California area that encountered significant quantities of methane (CH4) and hydrogen sulphide (H2S). Deliberate and very assertive Safety and Health measures were needed to collect, control, measure, process (i.e. dilute) and dispose of large quantities of naturally occurring gas. The gas was hosted under hydrostatic pressure, typically dissolved in groundwater and hydrocarbon deposits and released as mechanical excavation disturbed the ground mass that was initially under hydrostatic pressure, followed by TBM face pressure and later reduced to atmospheric pressure during tunnel spoil handling operations. Both gases are extremely hazardous and result in very challenging (dangerous) tunnelling conditions if not properly controlled throughout the entire excavation, ventilation and material handling stages.

In some areas, naturally occurring asphalt "seeps" impregnate the soils strata, adding to the spoil handling and disposal considerations. Please refer to Figure 63 below that illustrates the typical subsurface conditions in many portions of the Los Angeles area.

Typical subsurface conditions encountered in many portions of the Loa Angeles area. Note the location and orientation of the hydrocarbon deposits impacting tunnelling operations. These released methane and hydrogen sulphide gas in variable quantities and concentrations into the tunnel as the heading advanced. (Courtesy of Byron Ishkanian).

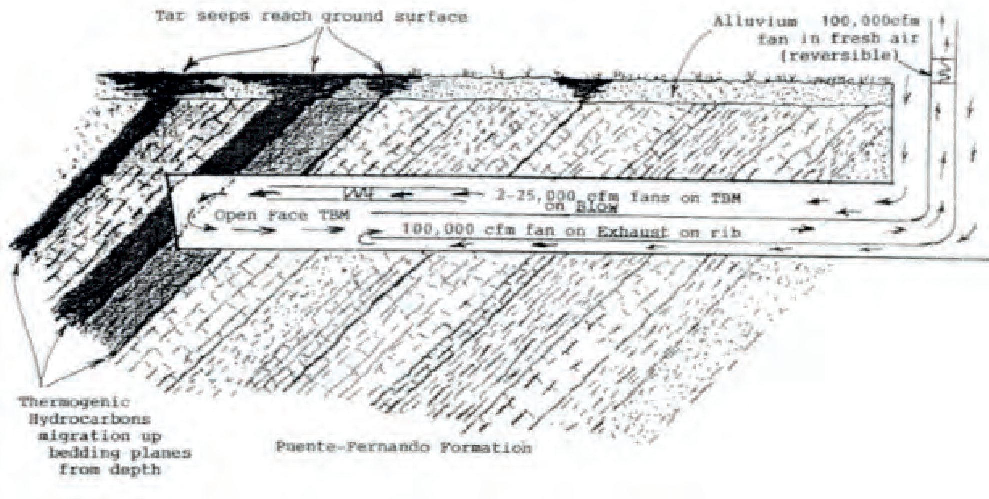


Figure 63: Los Angeles Area Subsurface Conditions – Puente-Fernando Formation.

Whereas the gases will naturally disperse once released to atmospheric conditions, both gases go through combustive and explosive stages (concentrations) until finally diluted and rendered, "safe and non-hazardous" (at very low, sustainable concentrations). Please refer to the book, "Hazardous Gases Underground, Applications to Tunnel Engineering" by Barry Doyle as listed in Section 14 – References and Additional Reading Materials. Please also refer to the preceding Section 5 – Health and Safety Aspects of Tunnel Spoil Materials for a discussion on methane and hydrogen sulphide gas encountered while tunnelling.

The following subsections briefly describe a fatal event and that occurred in the Los Angeles area that subsequently initially an important and far-reaching revision to federal and state regulations (i.e. CalOSHA Tunnel Safety Orders that have become the standard of the US tunnel industry) applied to all tunnelling projects and in particular, those that encounter gas, combustible and flammable materials in the ground and groundwater.

9.5.1 Sylmar, California – Tunnel Disaster, 1971

A disastrous gas explosion in a tunnel under Los Angeles in 1971 took the lives of 17 workers in a Metropolitan Water District tunnel beneath Sylmar, California (Figures 64 and 65). Please refer to the Appendices in Section 15 for more descriptive information. Construction was halted for two years while the Owner, the contractor and OSHA decided how to resume work and proceed safely. Many warning signs preceded the event but were not fully acknowledged or addressed. A criminal trial for negligence and new California Tunnel Safety Orders (TSOs) resulted in more strict tunnelling procedures. Tunnelling in areas where hydrocarbons are present now require special precautions and special procedures as articulated in the TSOs.

Following the Sylmar Tunnel disaster, the State of California, Department of Safety and Health rewrote and republished their ***"Tunnel Safety Orders".***

Cal/OSHA - Division of Occupational Safety and Health
https://www.dir.ca.gov/dosh

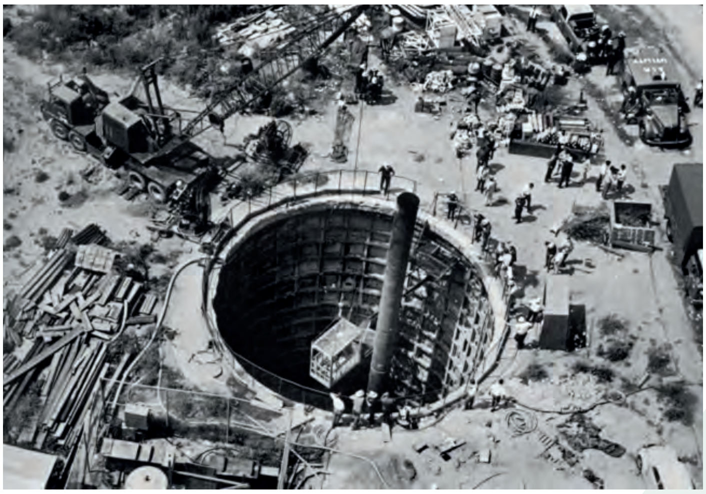


Figure 64: Sylmar Tunnel – Access Shaft
Aerial view of the access shaft at the Sylmar Tunnel following the fatal tunnel explosion in 1971. (Courtesy of Los Angeles Times)

Figure 65: Sylmar Tunnel – Evacuations
Evacuation of tunnelling personnel from the access shaft at the Sylmar Tunnel following the fatal explosion. (Courtesy of Los Angeles Times)

9.5.2 California Tunnel Safety Orders

The following abbreviated excerpts originate from the California Tunnel Safety Orders and are the most current regulations applied to all tunnelling and underground construction work performed in the State of California, United States.

§8403. Scope and Application [of the California Tunnel Safety Orders]

(a) In accordance with the provisions of Labor Code, Division 5, Part 9, et al., these orders establish minimum safety standards in places of employment at tunnels, shafts, raises, inclines, underground chambers, and premises appurtenant thereto during excavation, construction, alteration, repairing, renovating or demolishing and the following:
(1) Cut-and-cover operations such as subway stations which are both physically connected to ongoing underground construction operations and are covered in such a manner as to create conditions characteristic of underground construction.
(2) Boring and pipejacking operations 30 inches in diameter or greater in size. Exceptions: These safety orders do not apply to utility natural gas pipelines subject to the jurisdiction of the California Public Utilities Commission or the U.S. Department of Transportation, Office of Pipeline Safety, where a person does not bodily enter the bore during boring or pipejacking operations.
(3) Pipelines which are connected to and/or are an integral part of a tunnel where persons are working inside and the conditions are similar to a lined tunnel construction or repair project.
(4) All shaft excavations intended to exceed 20 feet in depth where employees may enter the shaft and/or approach the shaft area. A shaft will be considered a shaft from its inception. For shafts 20 feet or less in depth and excavations unrelated to the Tunnel Safety Orders, refer to, CCR, Title 8, Section 1533 and Article 6, commencing with Section 1539 of the Construction Safety Orders.

(b) With the following exception these orders take precedence at tunnels over any other safety orders of the Division that are inconsistent with them. Where employees work under the pressure of air in excess of atmospheric pressure, in connection with tunnel work, the Compressed Air Safety Orders also apply and take precedence over any Tunnel Safety Orders that are in conflict.

(c) Machines, equipment, processes and operations not specifically covered by these orders shall be governed by all other applicable general safety orders contained in Title 8, California Code of Regulations.

For additional discussions on the collection and management of hazardous gases including methane, please refer to the Case Study on the Sparvo Tunnel (Section 8.5) and Section 14 – References and Additional Reading Materials.

With all that has been said above, it is clear that the last thing a tunnelling Contractor should do it to contaminate the soil with materials used in the excavation process. Different tunnelling techniques can contaminate soils in differing manners and specifics are laid-out in the following sections. In general terms, all products and materials brought onto the jobsite must be carefully assessed for their potential environmental impacts, in addition to any potential Health and Safety issues. Should any of these materials spill or leach into the ground, what would be the repercussions…?

- Environmentally
- Financially
- From a Health and Safety perspective
- From a worker or project schedule lost-time approach

For tunnelling works in general, care needs to be taken in the control of contamination from material such as the following:

- Cement and concrete hardened and powder
- Oil and grease leakages from plant and equipment
- Leaks from material storage areas improperly bunded

In recent years, it seems to be becoming more and more common for TBMs to launch and be received into grout blocks, sometimes cross passages too are pre-grouted from surface. In Singapore for example, the entire length of some tunnel alignments has been "improved" by Deep Soil Mixing prior to the launch of the TBM. The resultant soil would clearly be highly contaminated with cementitious materials.

Most TBMs leak small quantities of oils and greases into the soil as part of their operation. For example, bearing greases purge themselves through the seals of the main bearing to prevent the ingress of soil into the seals, thereby damaging the bearing. It is, therefore, imperative to ensure that all oils and lubricants (i.e. grease) are both biodegradable and exhibit low eco-toxicity. In France, there was an issue where molybdenum was purged into the soil causing all the soils to be rendered "hazardous".

Nowadays, most TBMs worldwide use bi-component grout to backfill the annular gap surrounding the precast segmental tunnel lining. Both A and B components are highly basic and leaks are commonplace, either through the tail-brushes into the invert, from the tunnel pipelines or even around the TBM annulus and into the cutterhead chamber.

Other than grouting from surface, it is somewhat common in unstable ground conditions to grout from within the TBM through purpose made grout injection ports. There are many chemicals on the market to facilitate this kind of grouting operation. The objective could be to consolidate ground, prevent water or to fill a void. It is important to ensure that the grouting material is not going to contaminate the ground or groundwater while achieving its primary purpose.

10.1 SLURRY-FACED TBMS

Slurry TBMs typically excavate using bentonite powder in solution to control face stability and aid the transportation of the excavated spoil. To enhance the rheological properties of the bentonite slurry, there are a range of chemical additives that are often mixed with the slurry. All but a few bentonites have soda ash and polymers are added at source to improve the flow and other properties. The concentrations of these additives are relatively low, but care needs to be taken with disposal of tunnel spoil from a pH perspective as some bentonite-based slurries can rise over 10.

The excavated material from slurry TBMs is normally segregated into different size fractions owing to the design of TMP and the corresponding solids separation plant. Therefore, (we are assuming) contamination would most likely only become a serious problem in the discharge from filter-presses or centrifuges. The size categorization of this portion of the tunnel spoil does, however, lend itself to potential recycling applications within the slurry pumping circuit.

The chemicals often used in slurries are very well summarised in the AFTES Report on "Slurry for Use in Slurry Shield TBM" [16]. Some slurry machines use Attapulgite Clay in lieu of bentonite where there is saltwater, some use pure polymers and some, nothing such as used for the Arrowhead and OARS tunnel projects described under Section 8 – Case Studies of Tunnel Excavation. All should be checked for contaminants and potential to pollute.

Often the excavated soil from the tunnel is considered too wet for immediate off-site transportation or compaction. It is relatively common to add cement, lime, natural or synthetic polymers to the spoil to overcome this, either on a belt conveyor or outside the tunnel. Care must be taken to ensure that the addition of these materials is well mixed and does not render the spoil contaminated or hazardous.

Careful consideration for reprocessing and repurposing tunnel spoil originating from a slurry faced TBM should be analysed early in the project design development stages with a full knowledge of bentonite mixes (and additives) as well as the in-situ tunnel spoil properties (and behaviours).

10.2 EARTH PRESSURE BALANCED (EPB) TBMS

Not all ground conditions in their natural state have ideal characteristics for EPB tunnelling. When ground type(s) encountered by the TBM do not have the preferred (or ideal) characteristics of fluidity and plasticity required to maintain face stability or for spoil conveyance needs, ground conditioning materials (i.e. water, bentonite, foams and polymers, etc.) and procedures can be used to modify and improve the ground to better adapt the in-situ ground conditions to best suit the TBM design and operation and correspondingly, transmit sufficient confinement pressure to maintain face stability.

Typically, TBM operations need to make use of conditioners and variable operating parameters to best accommodate typically heterogenous ground conditions for successful TBM advance even in soils containing gravel, sand and silt or water, or in highly unstable geological conditions. Successful tunnel excavation can be greatly enhanced by the use of soil conditioning measures at the face and in the screw auger. This results in dramatic changes to the plasticity, texture and water permeability of the soil. Figure 65 below graphically illustrates the application of Earth Pressure Balance (and Slurry Face) tunnelling of a function of the anticipated grain size. Please see the grain size chart shown below in Figure 66.

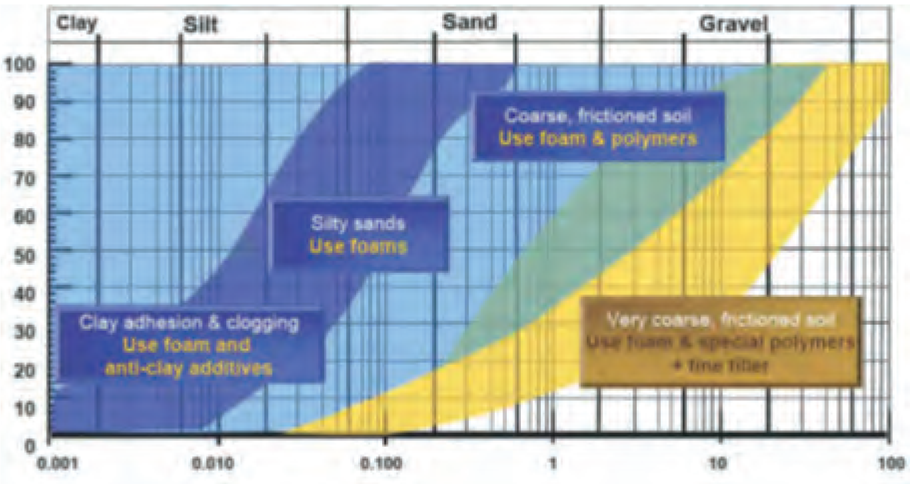


Figure 66: Soil Gradation Curve

Typical soil gradation curve for the application of various soil conditioners in Earth Pressure balanced tunnelling operations.

Advantages

- Ability to mix with soil
- No separation plant required (require for slurry systems)
- Reduction in machine wear
- Better face stability
- Improved EPBM versatility (<30% fines)

Polymers and other chemicals are also often added to either the face, plenum, screw to help control such parameters as wear, lubrication, torque, fluidity, stickiness etc. Please see Section 12 – Additives and Industrial Chemicals Used in Tunnelling Operations for more information related to these materials. Table 16 below illustrates some of the equipment and conditioning systems needed for efficient EPB tunnelling operations.

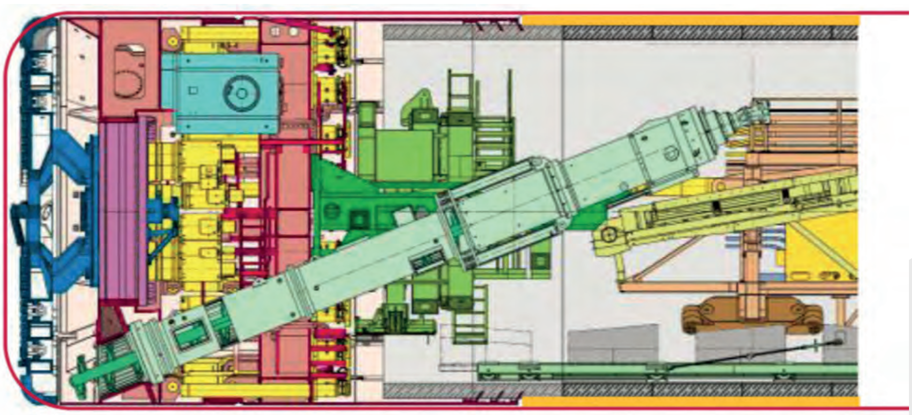


Figure 67: Cross-Sectional View of an Earth Pressure Balanced TBM

Cross-sectional view that illustrates the major systems and components of an Earth Pressure balanced TBM. The complexity and integration of major components is apparent; needed to maintain face pressure, spoil mixing while concurrently removing spoil at the same rate as excavation advance. (Courtesy of Herrenknecht AG)

It is fundamental that the supplier / producer of ground conditioning foam has current and credible environmental impact certification of their products from independent and accredited institutes or laboratories. It is also clear that the tests need to be carried-out at the same concentrations and on the same tunnel spoil, or else it would be easy to dilute the sample prior to submission for testing.

Careful consideration for reprocessing and repurposing tunnel spoil originating from an Earth Pressure Balanced TBM (Figures 67 and 68) should be analysed early in the project design development stages with a full knowledge of soil conditioning agents as well as the in-situ tunnel spoil properties (and behaviours).

Figure 68: Longitudinal Sectional View of an Earth Pressure balance TBM

General arrangement view of an Earth Pressure Balanced TBM and trailing gear that illustrates the major systems and components needed to support all operations. (Courtesy of Herrenknecht AG)

10 >> Contamination From Tunnel Excavation Activities

ITEM	TUNNING OPERATIONS AND EQUIPMENT IMAGES	COMMENTS
1		***Typical Factory Acceptance Tests*** Factory Acceptance Tests (FAT) using foam conditioners are shown • Demonstrating flow pressures and coverages around the TBM cutterhead. • Additional injection points included the plenum as well as multiple locations along the screw auger.
2		***Foam Injection System – TBM Trailing Gear*** Complex array of pumps, flow controls and metering devices for distribution of soil conditioning material as well as other chemicals. • Needed depending on actual and anticipated ground conditions encountered when using EPB equipment. • Highly variable mixing options, flow rates and pressures; as needed to adapt the heterogenous ground conditions. • PLC controlled
3		***Taipei Metro Tunnel*** Conditioner admixtures injected in the excavation chamber in the “right” proportions will produce tunnel spoil as seen in the image to the right. (Taipei Metro tunnel). • Highly plastic • Easy to handle • Contributes to rapid TBM advance
4		***TBM Holing Through – Foam Injection Demonstration*** Demonstration of the foam conditioner injection nozzles in operation following a TBM holing-through. • Not really an operational requirement, if only to demonstrate the continued functionality of the foam injection nozzles through the cutterhead. • Cutterhead wear can be reduced with the proper application of soil conditioners

Table 16: Earth Pressure Balanced Tunnelling Operations – Project Examples
Typical example of equipment and results tunnel spoil produced by Earth Pressure Balanced tunnelling operations starting with the Factory Acceptance Tests, trailing gears component and systems and the final output.

10.2.1 Brightwater East Tunnel – Seattle, Washington, USA

Tunnelling and ground conditions encountered at the Brightwater East Tunnel may be summarised as following based on the Case Study Report presented at the 2007 Rapid Excavating and Tunnelling Conference (RETC). Please see Section 14 0 – References and Additional Reading Materials.

“Tunneling through the North Creek Valley, the first 1,200 ft of tunnel, was a very critical and very closely scrutinized operation, due to very low cover and mining through normally consolidated soils, at times through partial or even full-face low shear strength, high compressibility peat and a Contract requirement to perform an intervention with a high water table.

The remainder of the tunnel was excavated through silts and sands, rarely clay. Ground conditioning played a very important role by conditioning the soil for torque and wear control while mining this difficult geology. The conditioned soil caused extreme cost overruns due to the water content and borderline pH. This was further exasperated by rising trucking costs and environmental agencies tightening the regulations and putting pressure on available dump sites. The end result caused the trucking costs to triple due to the rising dump fees, longer distances to haul and higher trucking rates due to the fuel crisis. Soil disposal has become a major cost and risk factor in EPB and slurry tunneling, especially in environmentally sensitive regions such as the Seattle area”.

For the Brightwater Tunnel, the encountered tunnel spoil modestly changes in its pH level concurrently stricter controls on the use of available local disposal sites. This resulted in severe threats to completion of the work as planned and scheduled. In retrospect a thorough evaluation of the ground water and spoil pH levels were needed before commencing work, in conjunction with a full understanding local spoil disposal regulations and available disposal sites.

11 >> DRAGON PROJECT (DEVELOPMENT OF RESOURCE-EFFICIENT AND ADVANCED UNDERGROUND TECHNOLOGIES)

Future tunnelling projects in Europe are expected to generate around 800 million tonnes of excavated material, which is usually disposed of in landfills. To turn tunnel spoil into a valuable resource for on-site reuse applications as well as other processes and sectors (cement, steel, ceramic, glass industries, …) a system for the automated online analysis, separation and recycling of excavated materials is necessary. The entire chain from characterization to classification and processing should be conducted completely underground. This process should be designed to save natural primary resources while also providing a high economic value. Another important objective is to assess the resource efficiency of different usage scenarios on a quantifiable basis and thus provide a basis for decision making by authorities [[39]DP-5].

For the DRAGON project, which lasted 36 months, and which was coordinated by Montanuniversität Leoben (MUL), seven partners from five different countries worked together to minimize the amount of landfill material resulting from tunnel excavation operations [[43]DP-9].

11.1 DRAGON PROJECT APPROACH

The technologies for the recycling of excavated material have strategic impact on sustainable management of limited mineral resources, higher resource efficiency through a recycling process, associated with a decreased European Union (EU) dependency on resource imports, less negative environmental impacts, more competitiveness for all companies and organisations associated with underground construction and new resource-efficient environmental technologies [[38]DP-4].

The aims of DRAGON were the development of advanced online technologies for the analysis of excavated materials as well as researching the significant parameters required for when raw materials are used in industrial processes. These parameters include grain size distribution, mineralogical composition, geochemistry, as well as water content and water absorption properties. At the same time advance rates should not be adversely affected by the new developments from DRAGON [[38]DP-4].

An automatic analysing system consisting of chemical, physical and mineralogical online analysis techniques was developed, all mounted on a bypass conveyor belt, which is fed by a hammer sampler [[41]DP-7]. A processing unit consisting of elements such as crushers, screens etc. is following the analysis system. In this way, the material can be prepared for reuse applications directly on-site or transported to be used as a raw material in other industrial sectors. All units are intended to be directly integrated into the Tunnel Boring Machine (TBM) so that the entire process of characterisation to classification and processing of the material should take place completely underground (Figure 69) [[38]DP-4].

11.2 DRAGON PROJECT BENEFITS

A main objective of DRAGON was to contribute to the conservation of natural resource within the EU. If the excavated material contains elements which are not currently attractive enough to mine due to their position in the host rock, geometry of the deposit or their low concentration, those elements could be separated from the "dead rock" in a selective manner and thereby, could allow the exploitation of new mineral deposits. The environmental protection potential due to the reduction of transport routes, the diminution of pollutants as well as the recycling of the excavation material will be another benefit which can be estimated by a Life Cycle Assessment (LCA). The main result of the LCA is to provide scientific evidence that the recycling of excavation material will result in more resource-efficient systems in Europe, also in context of circular economy [[38]DP-4].

Life Cycle Assessment (LCA) was conducted according to ISO 14040/14044 and includes Mass Flow Analysis according to Baccini and Brunner [[42]DP-8] as well as reduction of CO2 emissions for comparing different scenarios for the recycling or disposal of excavated material. After processing the material, it can be used in the raw material industry, as construction material, in agriculture, landfills or for disposal sites [[38] DP-4]. LCA researches the environmental impacts of the ingredients, the manufacture, distribution, use and disposal of a product.

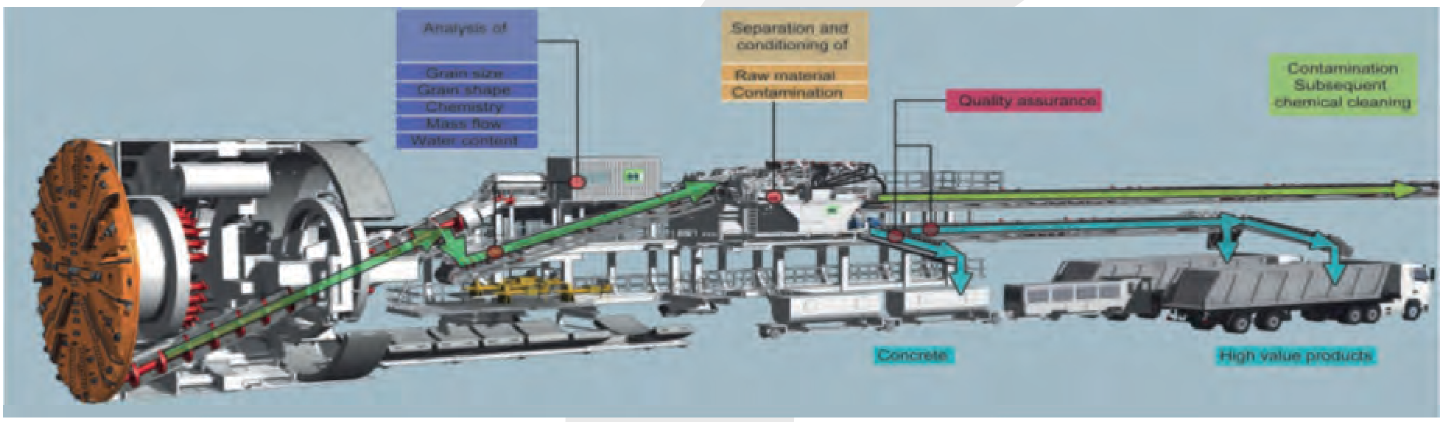


Figure 69: DRAGON Project – Online-Analysis and Processing Units - Prototype Development [[42]DP-8].

Therefore, input data of used resources like raw materials, electricity, fuels, water, ancillaries as well as transport from suppliers are compared to output data like product, co-products, solid waste, effluents and air emissions. The impacts of input and output substances are then analysed regarding their environmental impact like energy consumption, global warming, acidification, eutrophication, solid waste and photochemical smog [[41]DP-7].

Since the legal framework is not yet satisfactory, recycling of excavated material is only possible when spoil properties and the demand allow it are compatible. In addition, similar properties like geotechnical parameters and mineralogical composition as well as contamination must be taken into account, where a clear differentiation must be made between geogenous and anthropogenous contamination. If a legally binding rule states that excavation material is preferred for use as long as overall suitability can be demonstrated a new raw materials potential would be created and companies in the mineral raw materials industry would also obtain already partly processed material at favourable rates and preserve their existing quarries [[38]DP-4].

11.3 THE DRAGON SYSTEM

The continuous analysis of the excavation material will result in an objective geological documentation with a previously unknown extent, which offers the potential to avoid conflicts of the prognosis with the encountered conditions [[38]DP-4]. Other topics to be considered are:

- ***Economic Considerations:*** economic benefit comes from the earnings made by selling a material quality as well as from savings by substitution of otherwise purchased aggregates for the internal tunnel construction and by reduction of landfill costs. As soon as the sum of earnings and savings exceeds the cost of acquiring additional materials, the recycling of the material is considered profitable [[38]DP-4].
- ***Recycling Possibilities:*** if material meets the requirements for concrete aggregates, it should be directly recycled on site during the construction phase. If production of high-quality aggregates exceeds the demand on site, local producers and processors should be found as an alternative market. If lithology has indicated suitability for recycling as industrial minerals, the aim is to reuse the rock in mineral processing companies. If the material cannot be used for more high-quality applications, it can be used for landscaping on and off-site, as long as the legal framework permits it. If this is not possible the material has to be disposed of. The intention of recycling is not to be in competition with existing local raw materials companies but to make the material available at a reasonable price in order to save primary raw material deposits (Figure 70) [[38]DP-4].

According to the quality of the excavated material it can be subdivided into following reuse classes [[38]DP-4].

- Class 1: Reuse as construction raw material on site
- Class 1a: Reuse as construction raw material outside the site
- Class 2: Reuse as an industrial raw material – corresponding to a requirement catalogue of the mineral raw material industry
- Class 3: No higher-quality reuse
- Class 3a: Material for landscaping: embankment fill, backfilling, road sub-base etc.
- Class 3b: Landfill

11.4 PROCESS STEPS IN DETAIL

11.4.1 Some Technical Developments in the Project

Conveyor belts offer great opportunities for automated analyses, classification and processing of the excavated material since the measuring instruments can be installed directly onto the hauling installations [[38]DP-4]. On TBMs, a hammer sampler could feed a bypass on which the online analysis of the material takes place (Figure 71). Main parameters of the material in regard to its suitability as a resource are its grain size distribution and grain shape, water content, elemental composition, mineralogical composition, its amount of mica minerals and its strength parameters [[44]DP-10].

11.4.2 DCLM – Disc Cutter Load Monitoring

The physical characterisation of the geology ahead of a TBM can be described from the disc cutter force characteristics which leads to a better understanding of the relationship between rock parameters, rock mass strength, geology, cutting forces and cutter wear [[38]DP-4, [46]DP-12]. Furthermore, the Disc Cutter Load Monitoring (DCLM), in comparison to the standard Point-Load-Test, is a real-time measurement method and reliable under rough conditions [[41]DP-7]. Herrenknecht AG, together with Montanuniversität Leoben (MUL), have developed various methods for measurement of the cutter force on discs while boring (Figure 72) [[38]DP-4].

11.4.3 Automated Measuring of Grain Size and Grain Shape

To analyse grain size distribution, particle shape and particle number the excavated material is photo-optically analysed which results in a digitally evaluated image. Therefore, the material must consist of dry, non-agglomerating particles in the range from 10µm to 400mm (Figures 73 and 74). The rapid detection of particle size, particle shape and particle number as well as the reduced time compared to sieve analysis are the main advantages of photo-optical particle size analysis. [[38]DP-4].

11.4.4 Automated Analysis of Water Content of Material

As an online method to determine the water content of a continuous sample flow a microwave measurement has proven ideal since it measures the whole volume of a sample. It also represents a real-time measurement instead of the standard determination of the water content, which is done by drying in an oven until mass constancy [[41]DP-7].

11 >> DRAGON PROJECT (DEVELOPMENT OF RESOURCE-EFFICIENT AND ADVANCED UNDERGROUND TECHNOLOGIES)

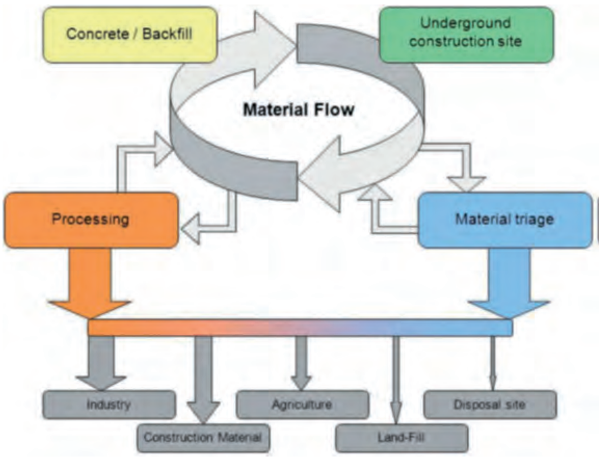


Figure 70: DRAGON Project – Material Flow Using New Analysis Separation and Recycling Techniques to Achieve Zero Waste [[38]DP-4].

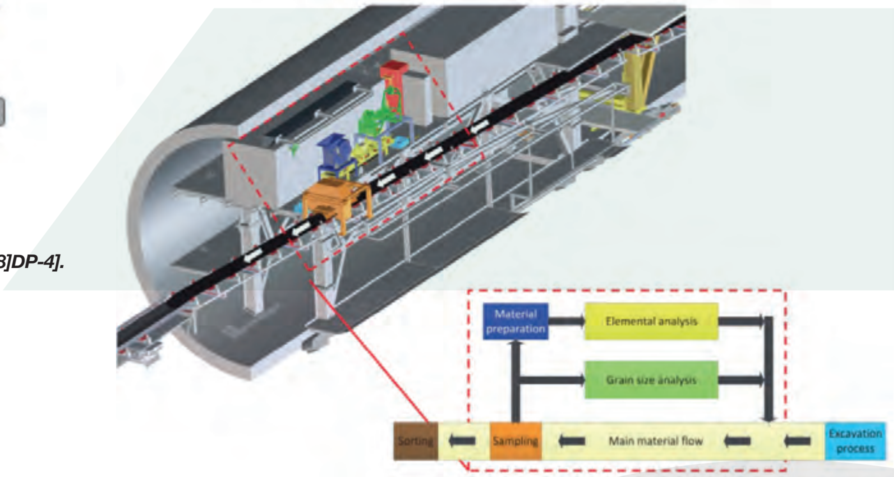


Figure 71: DRAGON Project – Prototype for the Automated Sampling, Bypass Analysis And Online Classification On TBMs [[42]DP-8].

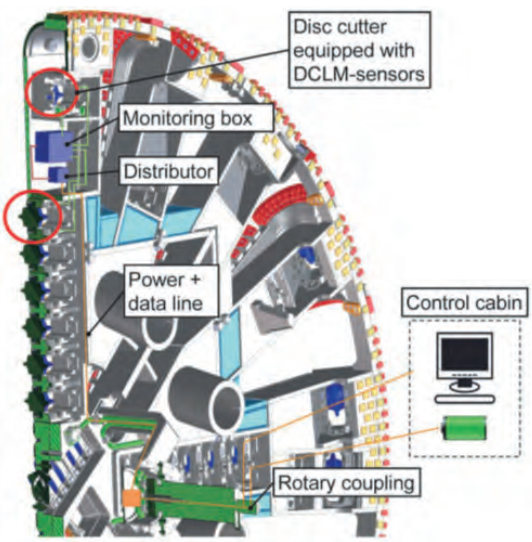


Figure 72: DRAGON Project –Implementation of the DCLM-System on a TBM [[42]DP-8].

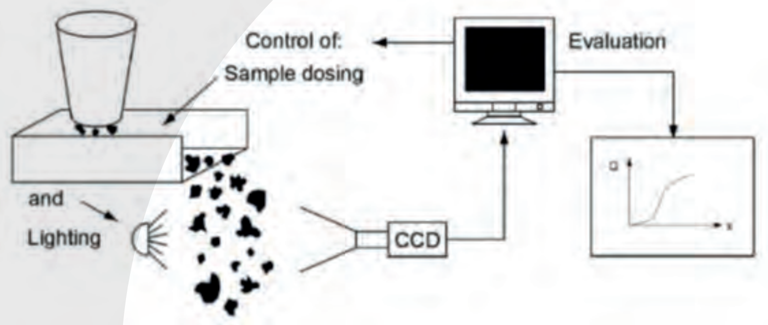


Figure 73: DRAGON Project – Instrumentation
Photo-optical system to determine grain size and shape [[38]DP-4].

Figure 74: DRAGON Project – Instrumentation
Photo-optical system to determine grain size and shape [[38]DP-4].

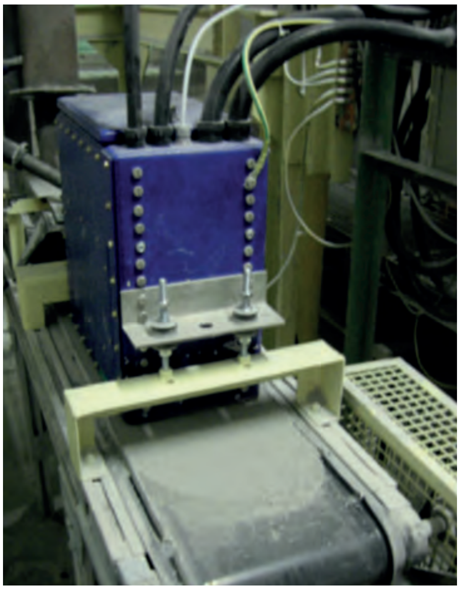


Figure 75: DRAGON Project – OXEA Online X-Ray Chemical Element Analyser (by Indutech) [[38]DP-4].

11.4.5 Automated Analysis of Chemical and Mineralogical Properties

X-Ray Fluorescence (XRF) spectroscopy is one of the most used analysis methods to determine the chemical composition of a sample. With XRF the exact elementary composition of materials can be measured qualitatively and quantitively (Figure 75). The XRF analysing unit is installed directly behind the particle size analyser [[40]DP-6].

Another important parameter concerning the mineralogical composition is the mica content of the excavated material in regard to its suitability as aggregates for concrete production. X-Ray Diffraction (XRD) offers an opportunity to conduct an online analysis of the mineral composition [[44]DP-10].

Aspects of material classification, material separation, material transport, material intermediate storage, material processing and material storage are key points for a successful reuse of the excavated material [4].

11.4.6 Materials Management

Aspects of material classification, material separation, material transport, material intermediate storage, material processing and material storage are key points for a successful reuse of the excavated material [4].

Material Processing

If the material is suitable for construction of support measures inside the tunnel, then it first has to leave the tunnel for processing and then transported back to the tunnel which causes increased electrical power consumption, complicated logistics, noise and dust nuisance as well as increased need for space in front of the portal. A mobile processing unit which is to be installed directly behind the tunnel face might be a worthwhile solution (Figure 76) [[38]DP-4].

Material Storage

Since tunnel construction projects have only limited capacities in intermediate or final material storage, it is a critical matter. The material should be stored separately according to its suitability to reuse applications respectively. This way, secondary mineral deposits are created [[40]DP-4].

11.5 Case Study Examples from the DRAGON Project

Since partners in DRAGON are involved in several underground construction projects with different prognoses of geology for each project they were chosen as Case Studies.

11.5.1 Railway Projects in Germany

In southern Germany, Porr, AG is involved in several major projects where a total of 26 km of tunnels produce 4.5 million tons of excavation material which feature a high content of gypsum, salt, and clay as well as sandstone. A clear separation of materials is the prerequisite of reusing the material as aggregates for concrete production as well as construction material for embankments, noise protection walls and diaphragm walls. Some materials also can be used in the ceramic industries while sandstone will mainly be used in the construction sector. An early detection of the chemical and morphological characteristics is important to increase the amount of useable material as well as sorting out material containing heavy metals which again could be used in the raw material industry [[38]DP-4].

11 >> DRAGON PROJECT (DEVELOPMENT OF RESOURCE-EFFICIENT AND ADVANCED UNDERGROUND TECHNOLOGIES)

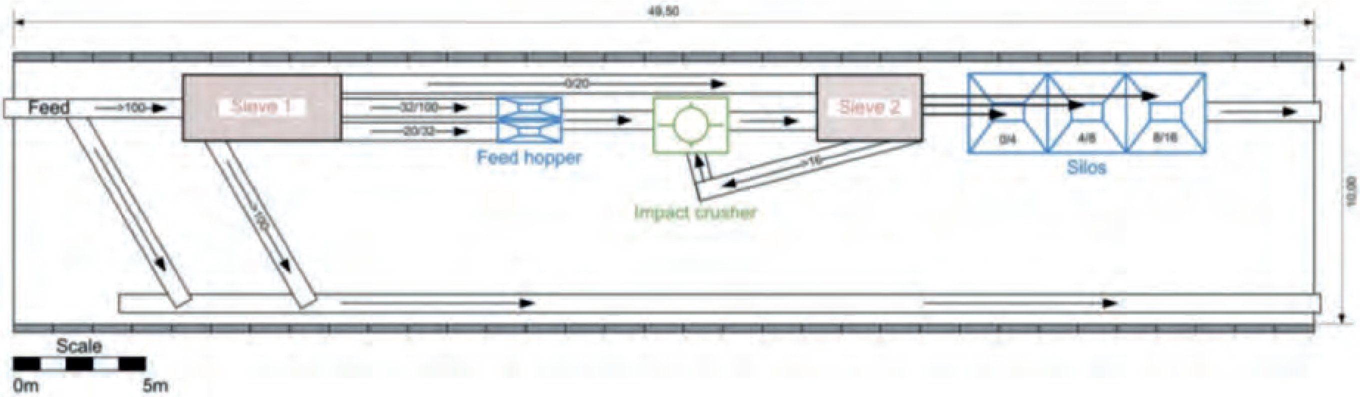


Figure 76: DRAGON Project – Material Processing Concept on the Back-Up of a TBM [[40]DP-6].

11.5.2 Lyon – Turin Tunnel between France and Italy

The main difficulty at this project which included about 250 km of tunnels and 35 million tons of excavated material, is the upcycling of the excavated material of difficult geology to produce some 12 million tons of aggregates from which about 6,000,000 m3 of concrete can be expected [[38]DP-4].

11.5.3 Nant de Drance Hydropower Project in Switzerland

The aggregates produced from material excavated by TBM and NATM is in complete accordance with the special requirements for high quality concrete for underground works. Both chemical and physical characterisation units as well as an in-situ shotcrete production unit was installed on the TBM. Further online measurement units were used in this project, like a DCLM for sandstone/siltstone characterization in the Bossler Tunnel and Saint Martín la Porte section as well as a chemical analysis in the Maurienne-Ambin Tunnel for SO3 detection [[38]DP-4].

11.6 PROJECT CONTEXT AND OBJECTIVES

During the DRAGON Project, a system of automated online-analysis techniques as well as units for the separation and recycling of excavated materials directly on the underground construction sites was developed. The results of the project will help to reduce or even eliminate material deposits thus aiming for the production of zero waste originating from underground construction sites. The Life Cycle Assessment performed provides scientific evidence that the implemented underground measures result in more resource-efficient systems and less CO^2 production.

Thus, the objectives of DRAGON were to develop new techniques in order to guarantee the following:

- Fast detection of useable mineral resources
- Immediate separation of excavation materials of varying qualities already within the underground construction site
- Processing of such excavation materials on the back-up system of the TBM
- Achievement of the economic optimum in the material management
- Supply of valuable mineral resources to industry situated nearby the particular underground construction site
- Minimization of land use or landfill capacity for disposal of excavation material.

12 >> ADDITIVES AND INDUSTRIAL CHEMICALS USED IN TUNNELLING OPERATIONS

As part of modern processes for tunnel excavation, grouting and ground support, including groundwater control, many additives and chemicals are commonly used. Several of these are briefly described below for a better understanding of their functions and benefits within various stages of tunnel and ground support (and ground improvement) operations. Cementitious and resin-based materials have not been included for simplicity. These materials are well addressed in separate references and supplemental reading materials many of which are listed in Section 14 – References and Additional Reading Materials.

12.1 POLYMERS

Polymers occur in almost limitless quantities in nature. In addition to naturally occurring polymers such as proteins or polysaccharides like starch or cellulose, polymers can also be synthesised by polymerization (i.e. polycondensation or polyaddition) [[10]BH-11, [[14]BH-92 and [[15]BH-93].

The chemical and physical properties of polymers are essentially determined by the physical properties of the monomers, the degree of polymerization and the structure of the chain molecules. The degree of polymerization is calculated from the number of monomers of a macromolecule; long-chained macromolecules have a higher degree of polymerization than short-chained. With an increasing degree of polymerization, the water bonding capacity of the polymer increases.

Polymers are mixed into bentonite suspensions to improve their flow, penetration and stability behaviour. Before using any additive, environmental acceptability and approval should be checked with the responsible authorities.

In the next section, polymers used as additives are categorised according to their function and chemical composition and described.

12.2 FUNCTIONS OF POLYMER ADDITIVES

Polymers are chemically active and can be divided into six functional groups for application as annular gap lubricants in pipe jacking [[9]BH-4, [[13]BH-44].

- Viscosity regulators (viscosifier)
- Filtrate reducers
- Clay stabilizers
- Thinners
- Mechanical fillers (lost circulation material)
- Lubricants

It is not possible to clearly delineate the individual properties in all cases since these often determine each other reciprocally. For example, viscosity regulation is associated with the formation of a gel, which at least hinders the loss of filtrate water into the surrounding soil. In addition, many polymers have different functions depending on the quantity used, since some of them can have a flocculation or gel formation action depending on the concentration.

12.2.1 Viscosity Regulators

In conventional lubrication suspensions, the bentonite itself is the basic viscosity regulator. Other viscosity regulators can be added to bentonite suspensions to build-up a gel structure and thus increase the viscosity. A polymer gel is a polymer network swelled in a fluid medium. The exact properties of this gel depend on the interactions between the network and the surrounding fluid.

One example of a polymer gel are hydrogels, which consist of a hydrophilic (water-loving) polymer with water as the hydration medium. The polymer network and the water molecules have a reciprocal affinity, through which the gel is stabilised. This affinity is caused above all by the hydration energy, which favours the attachment of water molecules. One example for such gelling agents is natural and modified organic viscosity regulators such as polysaccharides. These form stable hydrogels through the creation of hydrogen bridges.

Another type of gelling agent is associative viscosity regulators, which do not form a network on their own but by the attachment of particles that are already present in the fluid. These materials have both hydrophilic and hydrophobic properties. Examples are polyacrylamides and cellulose ether as well as hydrophobically modified polyacrylates.

Viscosity regulators can consist of for the following for example:

- Natural, organic (carbon-based) or anorganic (not carbon-based) molecules
- Modified organic macromolecules
- Synthetic macromolecules

Natural organic viscosity regulators are for example polysaccharides such as starch, Xanthan (xanthan gum) or Guaran (guar gum). Natural anorganic regulators are silicates such as bentonite itself.

Modified viscosity regulators are natural materials altered by chemical reactions to give them different chemical or physical properties. This includes, for example, various celluloses modified by a polymer reaction such as Methyl Cellulose (MEC), HydroxyEthyl Cellulose (HEC) or CarboxyMethyl Cellulose (CMC).

Synthetic viscosity regulators are substances such as polyacrylamide.

12.2.2 Filtrate Reducers

Filtrate reduction of suspensions denotes the reduction of the fluid quantity filtering into the surrounding ground [[9]BH-4] – the filtrate losses by forming the thinnest possible dense, tenacious and elastic sealing filter cake.

Filtrate reducers based on polymers consist of macromolecules, which are surrounded by a firmly adhering dense hydrate casing as a result of the large number of negative charges on their surface and their affinity with water. This reduces the size of the interstices between the clay particles for filter cake formation and also reduces the permeability of the filter cake and the filtrate quantity. The permeability of the filter cake is also reduced by the installation of freely present polymer particles, which can fill any pores that are still present as a result of their mobility and plasticity [[9]BH-4, [14]BH-92].

The basic function of filtrate reducers is thus mechanical and physical filling of the pores of the filter cake. The filtrate loss reduces exponentially with increasing concentration under constant conditions (pressure, temperature etc.). This means that zero filtrate is not achievable, even with very high polymer concentrations [[9]BH-4,

[14]BH-92]. Some examples of filtrate reducers are starch, CarboxyMethyl Cellulose (CMC) or Polyanionic Cellulose (PAC) [[9]BH-4].

Low filtrate water loss means not only less water loss from the bentonite suspension into the surroundings. The sealing effect of the filter cake also makes movement in the other direction more difficult, so less deleterious materials can get into the bentonite suspension. In this way, improved stability of the suspension can be achieved.

12.2.3 Clay Inhibitors

Another function of the filtrate reducers CarboxyMethyl Cellulose (CMC), Polyanionic Cellulose (PAC) or Hydroxyethyl Cellulose (HEC) is clay inhibition in ground with clay content (clay, loam, shale). This describes the effect that when the bentonite suspension comes into contact with the surrounding ground, the clay particles in the sides of the bored hole are prevented from absorbing water by the polymers. This minimization of water absorption by the clay particles prevents them swelling and thus counters any threat of the annular gap being squeezed.

The most effective clay-inhibiting polymers are Partially Hydrolysed PolyAcrylamide (PHPA) polymers from the families of the acrylates and acrylamides [[12]BH-41].

Since the bentonite suspension first comes into contact with the ground at the face, clay inhibition already has to be implemented in the bentonite suspension when the prevailing ground contains clay minerals capable of swelling. Due to the long stay time and thus the available reaction time, clay inhibition also has to be provided in the lubrication suspension in the annular gap, with the intention of preventing water absorption by any clay minerals capable of swelling in the sides of the bored hole. The excavated clay particle aggregates should also remain as compactly bonded as possible, in order to prevent further solution in the bentonite suspension.

When bentonite suspensions are prepared, clay-inhibiting polymers should only be added after complete hydration of the bentonite, otherwise there is a danger that the bentonite itself is prevented from absorbing water and swelling.

12.2.4 Thinners

In order to counter high viscosities and thus high flow resistance, thinners can be used. Thinners counter gel formation without thinning the bentonite suspension [[9]BH-4] and thus improve the flow properties of the suspension. These additives can, however, also reduce filter cake formation and reduce the filtration, counter salt effects and minimise the effect of the water on the formation.

Thinners generally contain relatively large anionic units, which are absorbed on the positive side of the clay particles and thus reduce the attraction forces between the individual particles, without affecting the hydration of the clay. Some examples of thinners are tannins, polyphosphates, lignites and lignone sulphonates.

12.2.5 Lost Circulation Materials

In ground with large pores and/or large fissures, loss of lubrication bentonite can be a problem. Depending on the cause of the loss of bentonite suspension, there are various effective measures to counter the reduction of the support pressure due to suspension flowing into large cavities or openings. The openings have to be blocked with lost circulation material in order to limit the flow of bentonite suspension into the ground.

Numerous substances can be used to provide this filling effect; examples are sawdust, shredded paper, bentonite granulate, confetti, coconut fibres or heavily swelling or networking polymers. Mixtures of two or three substances have often been used, so that mixes for specific uses are available.

In general, such materials are differentiated according to their physical properties as flakes, granulates or fibres. In some cases, for example when the pores are particularly large, a combination of the properties of different filler materials (e.g. size, consistency and strength) can lead to successful sealing.

12.2.6 Lubricants

First, the lubricating effect is normally achieved by supporting the annular gap or by the lubricating properties of the bentonite suspension. Should this not be sufficient in critical situations, products can be added to the bentonite suspension with a good lubricating or friction-reducing effect. Such additives are often based on waxes or natural oils such as rapeseed oil.

12.3 TYPES OF POLYMER ADDITIVES

12.3.1 Starch

Starch can be used in bentonite suspension in order to prevent filtration and thus water loss. Starch can be used in a saltwater environment, in which normal bentonite fails. It should be noted that starch, as a naturally occurring polymer, can be decomposed by numerous micro-organisms, such as bacteria [[9]BH-4]. In order to prevent this, the bentonite suspension can either be adjusted to a high pH value of ≈12 or biocides can be added. Starch can also be destroyed by the heat of agitation. As with many other organic polymers, starch is co-precipitated by the presence of calcium. Starch is non-ionic and shows no interactions with electrolytes. The physical properties of a starch suspension are given in DIN EN ISO 13500 - Petroleum and Natural Gas Industries Drilling Fluid Materials Specifications and Tests. [[11]BH-24]. Please refer to Table 17 below.

12.3.2 Xanthan

Xanthan (or Xanthan gum) is a polysaccharide formed by Xanthomonas campestris and a few related species of micro-organisms. Xanthan consists of d-glucose, d-mannose and d-galacturonic acid in a molar ratio 2.8:2:2.

The polysaccharide is characterized by its good solubility in water and forms a solution with high viscosity, which has pseudoplastic properties. In addition, the viscosity of Xanthan and gels containing xanthan is largely temperature independent. Xanthan can create gel strength and is thus the only polymer which reacts thixotropically like bentonite.

ITEM	PROPERTY AND CONDITION	PUBLISHED REFERENCE STANDARD a)
A	DISPLAY ON A VISCOMETER SCALE AT 600 MIN^{-1}	
1	In 40 g/l 40 g/l (5.34 oz/gal) salt water	≤18
2	In saturated salt water	≤20
B	FILTRATE VOLUME	
1	Filtrate volume in 40 g/l (5.34 oz/gal) salt water	≤10 ml (0.338 oz)
2	In saturated salt water	≤10 ml (0.338 oz)
C	RESIDUE LARGER THAN 2,000 MM (0.078 INCH)	no residue

Special Notes:
a) All data is related to the API rotating viscometer according to API RP 13B-1 Section 4.3 or the API filter press according to API 13B-1 Section 5.2.1 [[8]BH-2] in the standard test (see Section 5.4).

Table 17: Physical Properties of a Starch Suspension
Physical properties of a starch suspension according to DIN EN ISO 13500, "Petroleum and Natural Gas Industries Drilling Fluid Materials Specifications and Tests" [[11]BH-24].

ITEM	PROPERTY AND CONDITION	PUBLISHED REFERENCE STANDARD a)
A	CONTENT OF STARCH, GUAR GUM OR THEIR SUBSTITUTES	0 %
B	WATER CONTENT	≤13 %
C	SIEVE ANALYSIS	no residue
1	<425 MM (0.0167")	≥95%
2	<75 MM (0.0029")	≥50%
D	VISCOSITY a)	
1	Rotating viscometer, 300 min^{-1}	≥11 cP (scale value ≥55)
2	Rotating viscometer, 6 min^{-1}	≥180 cP (scale value ≥18)
3	Rotating viscometer, 3 min^{-1}	≥320 cP (scale value ≥16)
4	Brookfield LV, 1.5 min^{-1}	≥1,950 cP

Special Notes:
a) For rotating viscometers with a f0.2 turn spring. R1/B1 configuration:
- for 300 min–1, cP is equal to scale value × 0.2
- for 6 min–1, cP is equal to scale value × 10.0
- for 3 min–1, cP is equal to scale value × 20.0

Table 18: Physical Properties of a Xanthan Suspension
Physical Properties of a xanthan suspension according to DIN EN ISO 13500, "Petroleum and Natural Gas Industries Drilling Fluid Materials Specifications and Tests" [[11]BH-24].

Xanthan in suspensions mainly serves as a suspending additive. Small concentrations of the biopolymer are already sufficient for this effect. Although it does not act as a filtrate reducer, it can be used together with filtrate-reducing substances like CMC and bentonite. The physical properties of a pure Xanthan suspension are given in DIN EN ISO 13500 - Petroleum and Natural Gas Industries Drilling Fluid Materials Specifications and Tests. [[11] BH-24]. Please refer to Table 18 below.

12.3.3 Guaran

Guaran (or Guar gum) is a natural viscosity regulator based on polysaccharide. It is obtained from the seeds of Cyamopsis Tetragonoloba (Guar bean). Addition of Guaran to bentonite suspensions has the effect of forming a highly viscous solution. At the same time, Guaran is also used to reduce the filtration rate and improve borehole stability.

The biopolymer shows good tolerance against salts and can thus be used in saline flushing and lye solutions. Guaran is, however, unstable to heat and degrades at temperatures above 65 C. Any increase of temperature also leads to a reduction of viscosity. Like starch, Guaran is also decomposed by micro-organisms unless this is prevented by a high pH value or the use of a biocide.

12 >> Additives and Industrial Chemicals Used in Tunnelling Operations

Small concentrations of Guaran flocculate the drill cuttings. Borate ions network the hydrated Guaran and lead to extremely viscous bentonite suspensions, even at low polymer concentrations.

12.3.4 Modified Celluloses (PAC, HEC, CMC)

Modified celluloses are mostly used as viscosity regulators, filtrate reducers and clay inhibitors. The use of various high molar masses (polymer lengths) can greatly increase the viscosity or also reduce it. The products are then mostly labelled with the additional description “Lo Vis” or LV for low viscosity and “Hi Vis” or “HV” for high viscosity.

PAC (PolyAnionic Cellulose) is the most-used polymer in this group. In addition to changing the viscosity and reducing filtration, it has a slight clay inhibition effect.

HEC (HydroxyEthyl Cellulose) is structurally similar to carboxymethyl cellulose (CMC) but is non-ionic and thus particularly effective for use as a viscosity regulator and filtrate reducer for saline solutions. The viscosity of HEC solutions increases with the molar mass of the polymer. Magnesium oxide stabilises the thickening effect of HEC. HEC solutions show a pseudo-plastic rheology, but do not have any noticeable gel strength.

Sodium CMC (CarboxyMethyl Cellulose) is an anionic polymer, which is adsorbed by clay particles. In small concentrations, CMC acts as a filtrate reducer. CMC suspensions are shear-reducing; i.e. they have a high viscosity at low shear rates. The viscosity falls with increasing temperature. With increasing salt concentration, the filtrate reducing and viscosity-increasing properties of CMC decrease. As already described for starch, CMC is also co-precipitated in the presence of calcium and magnesium.

12.3.5 Polyacrylamide / Acrylate

Polyacrylamide is a synthetic polymer, which is available with various molar masses. There are various substitute variants of acrylamide polymers such as polyacrylamide, polyvinyl alcohol, polyvinyl pyrrolidone or polyvinyl methyl ether.

The properties of synthetic polymers in a bentonite suspension are not only determined by their chemical composition, their structure and their molar mass, but also by the composition and temperature of the system, to which they are added. The same polymer can, therefore, act as a flocculent, but also reduce filtration losses when it is used in higher quantity [[9]BH-4].

This wide variability in the use of synthetic polymers demands, however, an extensive test phase to investigate its effect on the bentonite suspension. Sodium polyacrylates for example can be used as filtrate reducers, but this property is always limited by its sensitivity to calcium ions. Polyacrylamides also alter the viscosity of the suspension and additionally have a lubricating effect.

PHPA (partially hydrolysed polyacrylamides) are linear copolymers of acrylates and acrylamides. They show a strong clay-inhibiting effect. Further properties are to increase viscosity and control filtration. If the quantity added is too high, flocculated bentonite particles often appear in the flushing from the borehole.

12.4 OVERVIEW OF POLYMER ADDITIVES AND THEIR FUNCTIONS

Table 19 shows an overview of the most important properties of the most commonly used additives for annular gap lubrication. The target function is described as the “primary function”, for which the polymer is used and which often at the same time indicates the strongest effect of the relevant polymer.

The “secondary function” is the (mostly undesirable) side-function of the polymer; at the same time, it is often its weaker effect. The secondary function must be taken into account when using polymers in order to avoid undesired effects.

ITEM	PRODUCT	PRIMARY AND SECONDARY FUNCTIONS OF POLYMERS					
		VISCOSITY CHANGING	FILTRATE REDUCTION	CLAY INHIBITION	GEL STRENGTH	SALT RESISTANCE	BACTERIAL DECOMPOS'N
1	Bentonite	Primary	Secondary	Secondary	Primary	-	-
2	Starch	Secondary	Primary			Yes	Yes
3	Xanthan	Secondary	Secondary		Primary	Yes	Yes
4	Guaran	Primary			Secondary	Yes	Yes
5	PAC	Secondary	Primary	Secondary			
6	CMC	Secondary	Primary	Secondary			
7	HEC	Primary	Primary	Secondary	Pseudo-plastic	Yes	
8	Polyacrylamides	Primary	Secondary			Slight	
9	PHPA	Secondary	Secondary	Primary			

Table 19: Primary and Secondary Functions of Polymers
Primary and secondary functions of polymers and their resistance to salt and bacteria when used in bentonite suspensions for tunnelling applications.

13 >> Conclusions and Recommendations

The authors of this report would like to offer the following conclusions and recommendations regarding the handling, treatment and disposal options for all forms of tunnel and underground excavation spoil materials. These materials, while often considered as rock and soil, also include water, gases, odours, dust. Some spoil materials may be tainted with contaminants such as petroleum products and dry cleaning fluid [tetrachloroethylene (perchloroethylene or PCE)], have acidic or basic characteristics, or be subject to strict local regulations, measurement, and formal documentation for chain-of-custody for disposal options (i.e. bentonite and asbestos).

More regulations and more tunnels are being excavated every year, producing millions of cubic metres of rock, soil and water to be disposed of within legal and sustainably sensitive approaches. To date, there are no consolidated, global guidelines available to suggest how this may be achieved in an environmentally and socially responsible manner. Indeed, the DRAGON Project as described in Section 11 pointed-out the highly compartmentalized approaches within the countries of the European Union. Moreover, in the United States, there is currently a myriad of the federal, state and local statutes and regulations affecting the treatment final disposal options available for all forms of tunnel spoil materials that vary region by region. It is, therefore, the authors' recommendation that the ITA and other national tunnelling organizations work cooperatively to develop a road map for more consolidated global guidelines for the handling, treatment and disposal of tunnel spoil materials.

Sampling and Testing

Essential Health and Safety related material sampling and testing is required to fully assess gas(es), mineral and chemical contents of the anticipated tunnel excavation spoil materials. As the authors have confirmed, formal approvals for construction of tunnelling projects are conditional on successful pre-construction material and chemical testing. It is, therefore, the authors' recommendation that it cannot be overstated, the importance of building site specific safety and spoil material testing programs into the initial project concepts and designs. To this end, knowledge and a full assessment of health and safety exposures and risks and the supporting systems need to be firmly established from the «first scratch on paper» of the tunnel concepts.

Reporting Requirements

Many jurisdictions and regulators require frequent and comprehensive reporting for many aspects of treatment and disposal of tunnel spoil materials, including all solids, gases, dust and liquids as "products of excavation". Full timely fulfilment of permit-stipulations are mandatory for full compliance. It is not unusual for permit granting agencies and regulators to closely monitor (and audit) all reporting requirements and schedules.

Changes in Law

It has been the authors' experience that changes in law and regulatory authority may have an impact on the selection and use of tunnel spoil disposal options. Changes in law could include material property value limits (i.e. pH values and grain size composition). Interpretation and enforcement of current and future legal restrictions and requirements will also have impacts on the handling, treatment and acceptable spoil disposal options.

Case Studies and Project Examples

Several Case Studies are presented that describe novel methods for handling, treating and disposing of products-of-excavation; i.e. solids, liquids and gases within the available technologies and site restrictions. As described in several cases, the combination of ground and groundwater conditions were so egregious that very creative site-specific means and equipment were developed and successfully implemented. In two cases, challenging subsurface conditions were further complicated with the presence of methane and hydrogen sulphide gas. It is, therefore, the authors' recommendation that the ITA and other national tunnelling organizations work cooperatively to develop a consolidated guideline and database describing and documenting innovative and successful handling, treatment and disposal of tunnel spoil materials (all forms) and especially where the solutions result in not only attractive "green solutions" but also utilize and enhance existing industries and develop new technologies. These goals would also score well for social and economic benefits.

Products of Excavation

As mentioned in the introduction to this tunnel spoils report, the content addresses many aspects of both mechanically and conventionally excavated tunnels and the resulting "products of excavation". Indeed, the preferred excavation method has significant impacts on the types and quantities of tunnel spoil materials needing treatment and final disposal options. This is not a new challenge and in one way or another, has confronted all tunnelling and underground construction projects; "what to do with the spoil material and groundwater". Indeed, some critically important project planning elements include the sampling, testing and recommendations for proposed mitigation measures related to tunnel spoil materials, long before any excavation has begun. It is, therefore, the authors' recommendation that during the project concept and design stages, careful (intensive) examination of the estimated quantities, anticipated spoil material composition, treatment and disposal options been rigorously addressed and assertively woven into the project approach with commitments from key stakeholders recorded in the Contract Documents. Success of some challenging projects could well depend on the conclusions, recommendations and advance commitments, permits and approvals.

Residual Chemicals

Additionally, legal and regional spoil

treatment and disposal regulations are increasingly restrictive on the use of industrial (biodegradable) chemicals frequently used for soil conditioning and ground improvement operations. The regulations have impacts that result in delays and deferments of significant and strategically important infrastructure project around the globe.

Reprocessing and Repurposing

In many proposed tunnel project locations, there is a strong (pervasive) interest in evaluating reprocessing (e.g. crushing and screening) and repurposing (e.g. backfills and land reclamation) opportunities for vast quantities of tunnel spoil material. While good examples of As-Built solutions are described in the enclosed Case Studies and project examples, more can be done. Use of matrix analyses, decision trees, quantity estimates, work-in-motion studies and advanced chemical and material processing analyses would potentially lead to many additional, attractive and economical solutions for reprocessing and repurposing of tunnel spoil. These critical reviews and goals need to be firmly embedded into the project design priorities and none regarded as "left-for-later" considerations.

14 >> References and Additional Reading Material

The following is a modest sampling of technical and regulatory references and additional reading materials in support of this paper. Many documents listed below contain still more relevant and valuable references that would be useful for developing a more consolidated approach to the challenges posed by handling, treatment and disposal of tunnel spoil materials.

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[2] DIN EN ISO 13500; "Petroleum and Natural Gas Industries Drilling Fluid Materials Specifications and Tests", Deutsches Institut Fur Normung E.V. (German National Standard).

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14.3 REFERENCE PUBLICATIONS

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[18] ISO 11348-3:2007; Water Quality — Determination of the Inhibitory Effect of Water Samples on the Light Emission of Vibrio Fischeri (luminescent bacteria test) — Part 3: Method Using Freeze-Dried Bacteria.

[19] Handling, Treatment and Disposal of Tunnel Spoil Materials, April 2019, Working Groups 14 and 15, International Tunnelling Association Report No.21. ISBN: 978-2-9701242-0-7

[20] OECD 301C – MITI Biodegradation Test (modified MITI - Ministry of International Trade and Industry, Japan) aerobic biodegradation test, Organisation for Economic Cooperation and Development.

14.4 SUPPLEMENTAL READING MATERIALS

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The following Appendices have been arranged to capture additional content related to selected preceding sections of this report. Specifically, they address more particular requirements for pre-construction environmental and material testing studies and corresponding permits and for the DRAGON Project that is focused on the use and repurposing of tunnel spoil material as well as the numerous regulations in the EU that affect and restrict the production of tunnel spoil material.

15.1 NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM (NPDES)

The NPDES permit program addresses water pollution by regulating point sources that discharge pollutants to waters of the United States. Created in 1972 by the Clean Water Act, the NPDES permit program is authorized to state governments by EPA to perform many permitting, administrative, and enforcement aspects of the program

- **What is an NPDES permit?**
  - The Clean Water Act prohibits anybody from discharging «pollutants» through a «point source» into a «water of the United States» unless they have an NPDES permit.
  - The permit will contain limits on what you can discharge, monitoring and reporting requirements, and other provisions to ensure that the discharge does not hurt water quality or people's health.
  - In essence, the permit translates general requirements of the Clean Water Act into specific provisions tailored to the operations of each person discharging pollutants.
- **What is a point source?**
  - The term point source is also defined very broadly in the Clean Water Act because it has been through 25 years of litigation. It means any discernible, confined and discrete conveyance, such as a pipe, ditch, channel, tunnel, conduit, discrete fissure, or container.
  - It also includes vessels or other floating craft from which pollutants are or may be discharged.
  - By law, the term «point source» also includes concentrated animal feeding operations, which are places where animals are confined and fed. By law, agricultural stormwater discharges and return flows from irrigated agriculture are not «point sources»
- **What is a pollutant?**
  - The term pollutant is defined very broadly in the Clean Water Act. It includes any type of industrial, municipal, and agricultural waste discharged into water. Some examples are dredged soil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste.
  - By law, a pollutant is not sewage from vessels or discharges incidental to the normal operation of an Armed Forces vessel, or certain materials injected into an oil and gas production well.
- **Do I need an NPDES permit?**
  - It depends on where you send your pollutants. If you discharge from a point source into the waters of the United States, you need an NPDES permit. If you discharge pollutants into a municipal sanitary sewer system, you do not need an NPDES permit, but you should ask the municipality about their permit requirements. If you discharge pollutants into a municipal storm sewer system, you may need a permit depending on what you discharge. You should ask the NPDES permitting authority.
- **How do NPDES permits protect water?**
  - An NPDES permit will generally specify an acceptable level of a pollutant or pollutant parameter in a discharge (for example, a certain level of bacteria). The permittee may choose which technologies to use to achieve that level. Some permits, however, do contain certain generic 'best management practices' (such as installing a screen over the pipe to keep debris out of the waterway). NPDES permits make sure that a state's mandatory standards for clean water and the federal minimums are being met.
- **Can the general public participate in NPDES permitting decisions?**
  - Yes. The NPDES administrative procedures require that the public be notified and allowed to comment on NPDES permit applications. When EPA authorizes a state to issue NPDES permits, EPA requires that the state provide the public with this same access.
- **How are the conditions in NPDES permits enforced by EPA and the states?**
  - There are various methods used to monitor NPDES permit conditions. The permit will require the facility to sample its discharges and notify EPA and the state regulatory agency of these results. In addition, the permit will require the facility to notify EPA and the state regulatory agency when the facility determines it is not in compliance with the requirements of a permit. EPA and state regulatory agencies also will send inspectors to companies in order to determine if they are in compliance with the conditions imposed under their permits.
  - Federal laws provide EPA and authorized state regulatory agencies with various methods of taking enforcement actions against violators of permit requirements. For example, EPA and state regulatory agencies may issue administrative orders which require facilities to correct violations and that assess monetary penalties. The laws also allow EPA and state agencies to pursue civil and criminal actions that may include mandatory injunctions or penalties, as well as jail sentences for persons found wilfully violating requirements and endangering the health and welfare of the public or environment. Equally important is how the general public can enforce permit conditions. The facility monitoring reports are public documents, and the general public can review them. If any member of the general public finds that a facility is violating its NPDES permit, that member can independently start a legal action, unless EPA or the state regulatory agency has taken an enforcement action.

- **What is the NPDES Permit Backlog?**
  - The Clean Water Act specifies that NPDES permits may not be issued for a term longer than five years. Permittees that wish to continue discharging beyond the five-year term must submit a complete application for permit renewal at least 180 days prior to the expiration date of their permit. If the permitting authority receives a complete application but does not reissue the permit prior to the expiration date, the permit may be «administratively continued.» For permits issued by EPA, existing permits are considered backlogged if EPA receives an application but does not reissue the permit prior to the expiration date. Additionally, applications for new EPA-issued permits are considered backlogged if not issued or denied within 180 days of receipt of the application. See NPDES permit backlog for more information.
- **Is it legal to have wastewater coming out of a pipe into my local receiving water (e.g., lake, stream, river, wetland)?**
  - As long as the wastewater being discharged is covered by and in compliance with an NPDES permit, there are enough controls in place to make sure the discharge is safe and that humans and aquatic life are being protected. To find out if a discharge is covered by an NPDES permit, call the EPA Regional office or the state office responsible for issuing NPDES permits.
- **Is there any information available to me on permits in my area?**
  - Yes, EPA's Enforcement and Compliance History Online (or "ECHO") website provides information on NPDES permitted facilities. You can search by your location to find NPDES permitted facilities near you. You can find out more about your local watershed through EPA's «Surf Your Watershed».
- **What are the primary differences between an NPDES individual permit and an NPDES general permit?**
  - A National Pollutant Discharge Elimination System (NPDES) individual permit is written to reflect site-specific conditions of a single discharger (or in rare instances to multiple co-permittees) based on information submitted by that discharger in a permit application and is unique to that discharger whereas an NPDES general permit is written to cover multiple dischargers with similar operations and types of discharges based on the permit writer's professional knowledge of those types of activities and discharges. Individual permits are issued directly to an individual discharger whereas a general permit is issued to no one in particular with multiple dischargers obtaining coverage under that general permit after it is issued, consistent with the permit eligibility and authorization provisions. As such, dischargers covered under general permits know their applicable requirements before obtaining coverage under that permit. Furthermore, obtaining coverage under a general permit is typically quicker than an individual permit with coverage under a general permit often occurring immediately (depending on how the permit is written) or after a short waiting period. Coverage under an individual permit may take six months or longer.
- **What does submittal of an NOI mean?**
  - A Notice of Intent (NOI) for a general permit is similar to a permit application, in that it is notification to the regulatory authority of a planned discharge for which coverage under a specific National Pollutant Discharge Elimination System (NPDES) general permit is needed and contains information about the discharge and the Operator of that discharge. The NOI serves as the Operator's notice to the permitting authority that the Operator intends for the discharge to be authorized under the terms and conditions of that general permit. By signing and submitting the NOI, the Operator is certifying that the discharge meets all of the eligibility conditions specified in the general permit (e.g., that a pesticide discharge management plan has been developed if necessary) and that the Operator intends to follow the terms and conditions of the permit. A fraudulent or erroneous NOI invalidates permit coverage. An incomplete NOI delays permit coverage until such time as the NOI has been completed.
- **How can I find out about a proposed permit for a facility near me so that I can participate in the permitting process?**
  - If a facility near you has applied for an NPDES permit, the permitting authority or company will have provided notice in a major local newspaper, usually in the legal section of the classified ads, or in an official publication such as the Federal Register. You also may call the appropriate state regulatory agency for information on applications for permits. For more information, refer to the Permitting Contacts section of this web site.

15.2 DRAGON PROJECT (REFERENCE SECTION 11) (Development of Resource-efficient and Advanced underGrOund techNologies)

15.2.1 Project Results

WP1 (Project Management)
The most important tasks of WP1 which were dedicated to Project Management were the set-up of the different project management bodies as well as the establishment of an efficient communication and monitoring structure within the DRAGON Consortium.
WP2 (End User Requirements)
The basic characteristics of the excavation materials to be checked "on-board" of the TBM were defined. In parallel work was started to set-up a mineral data base, which also included the possible industrial use of the particular mineral resource. Furthermore, the current legal regulations regarding the DRAGON concept where shown for numerous European countries.

WP3 (Material Analysis Techniques)
Improvements of the existing on-line analysing units were performed. Furthermore, a pneumatic lifting system for the OXEA has been developed. Significant results have also been achieved with the novel moisture meter. Last but not least, a feasibility study for a new method to determine low concentrations of heavy

elements, using XRF technology has been created.

One of the most important criteria for the recycling of excavated materials from TBMs is the rock strength. The approach regarding the automated on-line determination of the rock strength by online monitoring of the disc cutter load proved to be feasible. Therefore, the development of a Disc Cutter Load Monitoring was started and successfully tested on an actual TBM drive.

For the evaluation and classification of the excavated material the determination of the distribution of the grain size and shape is required. For the automated analysis of these parameters the technology from the company Haver & Boecker turned-out as the most feasible method. In cooperation between Herrenknecht and InduTech the main dimensions and features of the bypass belt conveyor as a preparation for the installation of the measuring devices were defined and the bypass conveyor belt realized in course of the prototype assembly.

WP4 (Material Recycling Process)

Within Task 4.1 of WP4, the consortium defined the relevant and minimum raw material processing requirements as well as the quality criteria for on-site use of hard-rock TBM muck as aggregate for various products like shotcrete. Further work was spent on the optimization of the cutting parameters based on the requirements for the use of the excavation material. Task 4.2 was focussing on a process description and quality criteria for automated processing of soft ground material compounds like Bentonite and gravel.

Main topics of that task were to find a new way for slurry classification and separation for Mixshields as well as the recovery of foam or water mixed to excavated material. Besides studying the mentioned principle techniques, work was spent on the automation of the separation of slurry and gravel as well as bentonite and slurry using already existing but also innovative new technologies for an automated soft ground processing prototype.

WP5 (Development of Prototypes)

After the design concept for the prototypes was finished in course of WP5 (Development of Prototypes) the relevant system components were specified in coordination with the development activities in WP3 and WP4. The assembly of the prototypes was accomplished by end of November 2014. During the review meeting in December 2014 in Schwanau the prototypes were tested and evaluated successfully.

WP6 (Demonstration)

Followed in the second reporting period. So for example: in September 2015 a demonstration event was held in Leoben to demonstrate the major outcomes and benefits of the project to interested parties within and outside the underground construction sector. The demonstration event was split in two parts: a theoretical part with presentations regarding the developments in each of the work packages and a practical part, which included a presentation of the disc cutter load monitoring, the mica determination and the mineral resources related tunnelling database.

WP7 (Impact on Environment and Resource Efficiency)

Activities in WP7 (Impact on Environment and Resource Efficiency) were linked to Life Cycle Assessments (LCA) activities. In this relation the DRAGON Consortium organized a joint event with representatives of 12 other FP7 projects dealing with the topic “resource efficiency”. The goal of that meeting was to share and to exchange knowledge on LCA. The overall outcome was very positive and resulted in some recommendations to the EU for managing environmental assessments within future projects so as to maximize the value of these studies. Furthermore, Life Cycle Assessments were performed for different usage scenarios, resource efficiency and environmental gains were shown, and the mineral resources related tunnelling database was developed in WP7.

WP8 (Evaluation Plan)

Within WP8 (Evaluation Plan) according to the project plan has been prepared and executed. The evaluation results are part of deliverable D8.3.

WP9 (Communications)

Regarding WP9 besides setting-up the project webpage (www.dragonproject.eu) and creating a factsheet for the public, work was spent on various dissemination activities (project video, project folder, etc.). Part of the dissemination activities were the presentation of the DRAGON project at national and international conferences and the publication of scientific papers in relevant magazines. Besides that, an exploitation plan including a market study was set-up.

15.2.2 Potential Impacts

Strategic Impact

Cross-European development, multidisciplinary working teams (geologists, mechanical engineers, safety and environmental experts, etc.) and integration of different resource-efficient environmental technologies strongly depend on the ability to cope with the inherent complexity of technologies and environments in order to boost organisational, national, international as well as individual performance and productivity. The DRAGON Consortium provided sufficient experience and scientific excellence in order to guarantee the successful implementation of the DRAGON project on a European level. The DRAGON project aimed to contribute to the general European strategy of

- Preventing waste
- Minimizing waste
- Re-using it as a new valuable raw material

Besides that, the business area of environmental and resource-efficient technologies is one of the fast-growing economic sectors in Europe and quite important for the pioneering role of Europe in relation with an environmental-friendly policy. The technologies developed in DRAGON in order to reuse the excavation material will have (in the future) a fundamental impact on:

- Sustainable management of limited mineral resources

- Higher resource efficiency through a recovery process and related decrease of EU dependency on resource imports
- Lower environmental impact; e.g. by slowing down other environmentally critical mining processes
- More competitiveness of all underground construction related companies/ organizations
- New resource-efficient environmental technologies.

The rate of utilization of excavated materials from tunnelling will be significantly increased. Besides increasing this rate, the goal of DRAGON is also to achieve valuable minerals which could be used for construction materials, steel production, ceramics, electronics, pigments and others. Austria for example plans to build 200km of tunnels during the next decade. About 35 million tons of excavation materials will be produced.

An increase of valuable utilizations for example up to 30% would already mean an economical advantage of approximately 50 million Euros. The aspired reduction of the disposed material to 20% would save 3.5 to 7 million cubic meters of disposal space and the same volume of open-cast mining with negative impacts on the environment could be reduced. Between 3.5 and 25 million Euros of disposal costs could be saved, depending on the negative ecological relevance of the material. Transferring this situation to entire Europe, these economic and ecological advantages could be multiplied with a factor ten to twenty. So, the total impact for Europe is expected to be between 500 million and 1.5 billion Euros.

Scientific Impacts

DRAGON aimed in a multi-disciplinary way at the optimization of the research outcome and commercial exploitation of its results by mobilising the critical mass of scientific knowledge as well as eco-environmental application skills.

Most of that expertise was already based on previous funded national projects and initiatives, in which some of the partners have been involved (e.g. one Austrian project (funded by FFG) which was dealing with the re-use of tunnelling excavation material and another German project (funded by DBU) which aimed at the development of an innovative separation technology for bentonite).

Novel and absolutely innovative technologies within DRAGON are:

- Control of a tunnel boring machine by the fragmentation of the excavated rock which led to an optimisation of the machine operation.
- Scientific challenges in the DRAGON approach were the combination of optical particle size measurements on a continuous sample and its evaluation with respect to the natural breakage characteristics.

Therefore, the connected scientific impact embraced technologies:

- Which allowed online-analyses considering grain size, grain shape, etc. under outstanding underground conditions
- Which allowed new separation processes
- Which facilitated recycling technologies of underground excavation materials under very limited space conditions.

Reducing the pressure on primary raw materials/preserving the environment/ reducing pollution The Domestic Material Consumption of the EU-27 as a whole is increasing. The biggest part consists of non-metallic minerals, especially sand and gravel. The exploitation of minerals is usually affected by conflicts between the economic interests of the extractive industries or the construction sector and environmental protection concerns, but also declining sizes of natural stocks have an influence. To overcome such problems new ways of making minerals available on a regional and local level through tunnel excavation projects is a possible solution. The excavation close to the users is very important because it will also help to reduce the consumption of fossil fuels for production, processing, and transport.

Additionally, DRAGON contributed to the European concepts to tackle the challenges in commodity markets and on raw materials (EC Raw Materials Initiative strategy document, February 2010) by helping to make Europe more independent from the markets in terms of metallic minerals, industrial minerals and construction materials.

Fostering the Use of Secondary Raw Material

The European economy heavily relies on resource imports and has a risky dependency on countries with difficult political, social and environmental circumstances especially when it comes to high-tech metals.

The substitution of such sources for primary raw materials by tunnel excavation materials was a new and innovative way to foster the use of secondary raw materials.

DRAGON also supported the third pillar of the EC Raw Materials Initiative by boosting resource efficiency and promoting recycling. By transforming underground construction projects into a kind of new and innovative mining places to gain new raw materials DRAGON fits well to the framework of the Europe 2020 flagship initiative on resource efficiency, which was presented by the Commission in 2011.

Building-Up on More Sustainable Consumption and Production Patterns

Resource efficiency also in the underground construction area is an important driver of innovation and a key element for achieving sustainable development and hence also sustainable consumption and production. The DRAGON project contributed to the idea that the most valuable material is already separated (within the underground construction area) from less valuable or even hazardous substances in order to re-use that material with the highest quality as possible and to immediately re-use/transfer the material into other industrial production cycles (either directly on the underground construction side and/or in other industrial sectors such as cement, brick, ceramic, glass, steel and other industries).

From the organisational side that have very positive effects on the future workflow in the underground construction industry area itself because the excavation material is directly processed and separated into different process streams according to the corresponding quality and does not need to be stored temporarily outside of the underground construction site. The missing space in the portal areas of underground construction sites is one of the main reasons why most of the excavation material is disposed instead of it is brought into other industrial production cycles.

Increasing the Role of SMEs as End Users and Developers of Green Technologies

The Consortium featured major participation of SMEs. That means that more than 50% of funding was dedicated to the Subject Matter Expert (SME) partners who were experts in a number of underground construction areas and active in so called niche markets. Their roles can be summarized as follows:

- Development of various high performance online analysis techniques
- Development of new and innovative materials management concepts as well as setting-up models for the optimal transportation, storage and handling/processing of the excavation material (= valuable raw material within other industrial production cycles).
- Analysis of environmental performance and Life Cycle Assessment (LCA).

Those fields of operation which were vital for DRAGON required a high degree of flexibility, innovation and expertise, properties which could be provided by the DRAGON SME partners.

The SMEs helped to disseminate the results among authorities and infrastructure operators for whom they normally work as independent underground construction experts. The knowledge they achieved through DRAGON will enhance their significance in their own projects and will provide new tasks for them in managing the material streams in a more sustainable and also in a more economical way. This kind of know how will strengthen their position in the national and international underground construction field.

The cooperation with the industrial parties like Herrenknecht and PORR, AG enabled those SME partners to widen their business contacts and to enter new markets.

Impact on Society and Environmental Impact

One of the main objectives of the DRAGON project was to contribute to the natural resource conservation within the European Union. The reduction of solid waste volume in a range of about 300,000,000 m3 going to the landfill (with associated road transport costs) was a desired impact of the project. Depending on the geological composition of the material it is possible to recycle up to 100% of the excavated material. The reduction of transport ways, the diminution of pollutants as well as the re-use of the excavation material possess a large environmental protection potential.

Besides that, another important impact was related to a significant reduction of the use of new raw materials (primary resources) which have an impact on global warming, on the acidification and eutrophication potential, on the stratospheric ozone depletion and on the Photochemical Ozone Creation potential.

The main expected outcome of the Life Cycle Assessment (LCA) was to provide scientific evidence that the re-use of excavated tunnelling material results in more resource-efficient and more closed-loop related systems (even in the industry-related economy) in Europe.

Contribution to Standards and Relationship to Important Stakeholders

The DRAGON Consortium aimed to establish a close relationship to the external surroundings (national environmental authorities; standardisation bodies etc.) of the project in order to implement and integrate the project results/findings quite smoothly within the specific regional, national and/or international environment.

Main target of the DRAGON project was to act as ***Best Practise Case*** how underground excavation material can be re-used as valuable material in diverse industrial processes and sectors. In that connection the DRAGON Consortium got in close contact with diverse national and European stakeholders (some of them were already part of the Advisory Board) and tried to influence the diverse directives in order to guarantee the re-use of underground extraction material as new valuable input material for other industrial processes and industries. Beside that ISO Standards: 14040/14044 for Environmental management – Life Cycle Assessments were used in order to include “life cycle thinking into the project”.

Why the Project Required a European Approach?

Statutory regulations concerning environmental technologies and waste management are currently governed by national authorities and are, therefore, completely non-homogeneous. The basic European vision towards finding a solution for the re-use of tunnelling excavation material is very well in-line with the idea to set-up international standards and to solve such a problem on an international level.

The European Commission is one of the predominant drivers for introducing sustainable resource management as well as innovative environmental technologies/solutions and to strengthen the position of Europe in the global market of environmental technologies. The European level is therefore the right “ecosystem” in terms of stipulating support from the national environmental authorities and to provide adequate visibility of those efforts.

The present approach needed many competencies from many different scientific, technological, environmental and geological fields. So for example, in order to develop new solutions which allowed the re-use of excavation material, the various underground conditions in Europe had to be examined. These embraced clay in London, which was the main geology at the huge underground project Cross Rail in UK to Alpine geological conditions, for example in the huge tunnel project Lyon-Turin between France and Italy. DRAGON intended to use especially the above-mentioned underground construction projects as valuable case studies.

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15.3 ARROWHEAD TUNNEL PROJECT – ENVIRONMENTAL REQUIREMENTS FOR WATER DISPOSAL

The Arrowhead Tunnels Project located in San Bernardino, California was a landmark project; due to extremely difficult geological conditions but also due to the strict environmental controls and regulatory requirements. The following is an excerpt from Contract Section 01066 – Environmental Requirements for Water Discharge; reporting requirements.

15.3.1 Reporting

A. By January 20 of each year, the Contractor shall submit an annual report to the Engineer. The report shall contain both tabular and graphical summaries of the monitoring data obtained during the previous year. In addition, the Contractor shall discuss the compliance record and the corrective actions taken or planned which may be needed to bring the discharge into full compliance with the waste discharge requirements.

B. The Contractor shall submit monitoring reports within 10 days of the beginning of each month and shall include:
• The results of all chemical analyses for the previous month, and annual samples whenever applicable
• The daily flow data
• A summary of the month's activities

C. All reports shall be arranged in a tabular format to clearly show compliance or non-compliance with each discharge specification.

D. For every item where the requirements are not met, the Contractor shall submit a statement of the actions undertaken or proposed which shall bring the discharge into full compliance with requirements at the earliest time and submit a timetable for correction.

E. The Contractor shall report the results of the above analyses to the Engineer within 24 hours of finding any discharge that is in violation of the discharge specifications.

F. The results of any analysis of samples taken more frequently than required at the locations specified in the Monitoring and Reporting Program shall be reported to the Engineer.

G. If no discharge occurs during the previous monitoring period, a letter to that effect shall be submitted by the Contractor, in lieu of a monitoring report.

H. All applications, reports, or information submitted to the Engineer shall be signed and certified in accordance with 40 CFR 122.22.

I. The Contractor shall file with the Engineer a report of waste discharge at least 100 days before making any material change or proposed change in the character, location, or volume of the discharge.

J. The Contractor shall give advance notice to the Engineer as soon as possible of any planned physical alterations or additions to the permitted facility.

K. The Contractor shall give advance notice to the Engineer of any planned changes in the permitted facility or activity that may result in noncompliance with these waste discharge requirements.

L. Noncompliance Reporting
• The Contractor shall report to the Engineer any noncompliance that may endanger health or the environment, as soon as the Contractor becomes aware of the circumstances. A written report shall be submitted within 5 days and will contain a description of the noncompliance and its cause; the period of noncompliance, including exact dates and times and, if the noncompliance has not been corrected, the anticipated time it is expected to continue; and steps taken or planned to reduce, eliminate, and prevent reoccurrence of the noncompliance.
• The Contractor shall report the following within 24 hours:
- Any upset that exceeds any discharge limitation
- Any violation of a maximum daily discharge limitation for any of the pollutants listed

M. The Contractor shall submit to the Engineer a written report within 60 days after the average water flow for any month equals or exceeds 75 percent of the design capacity of treatment and/or disposal facilities. The report shall include:
• Average daily flow for the month, the date on which the instantaneous peak flow occurred, the rate of that peak flow, and the total flow for the day
• The Contractor's best estimate of when the average daily dry-weather flow rate shall equal or exceed the design capacity of his facilities
• The Contractor's intended schedule for studies, design, and other steps needed to provide additional capacity for this waste treatment and/or disposal facilities before the waste flow rate equals the capacity of present units

N. The Contractor shall notify the Engineer as soon as the Contractor has reason to believe:
• That any activity has occurred or shall occur that would result in the discharge of any toxic pollutant, if that discharge will exceed the highest of the following notification levels:
- One hundred micrograms per liter (100 µg/l)
- Two hundred micrograms per liter (200 µg/l) for acrolein and acrylonitrile; 500 micrograms per liter (500 µg/l) for 2,4-dinitrophenol and 2-methyl-4,6-dinitrophenol; and one milligram per liter (1 mg/l) for antimony
- Five times the maximum concentration

value reported for that pollutant in the permit application
- The level established in accordance with 40 CFR 122.44(f)
- That they have begun or expect to begin to use or manufacture as an intermediate or final product or byproduct any toxic pollutant that was not reported in the permit application

15.3.2 Quality Assurance

A. The Contractor shall inform the Engineer of any material change or proposed change in the character, location, volume, treatment or disposal methods of the discharge.

B. The Contractor shall at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances) which are installed for compliance with the Basin Plan and the WDR/NPDES Permit. Proper operation and maintenance include effective performance, adequate resources, adequate staffing and training, adequate laboratory and process controls and appropriate quality assurance procedures. This provision includes the operation of backup or auxiliary facilities or similar systems. All systems, both those in service and reserve, shall be inspected and maintained on a regular basis. Records shall be kept of the inspection results and maintenance performed and made available to the Engineer. All of the above procedures shall be described in an O&M Manual. The O&M Manual shall also contain a description of the safeguards to assure that no spillage occurs should there be a reduction, loss, or failure of electric power.

C. The O&M Manual shall describe preventive (fail-safe) and contingency (cleanup) plans for controlling accidental discharges, and for minimizing the effect of such events. These plans shall identify the possible sources of accidental loss, untreated or partially treated wastes bypass, and polluted drainage. Loading and storage areas, power outage, waste treatment outage, and failure of process equipment, tanks and pipes shall be considered.

D. Solids, sludge, filter backwash, and other pollutants removed in the treatment or control of construction water shall be disposed of in the manner approved by the Engineer.

E. The following shall not be introduced into the treatment works:
• Wastes that create a fire or explosion hazard in the treatment works
• Wastes that cause corrosive structural damage to treatment works, but, in no case, wastes with a pH lower than 6.5 unless the works are designed to accommodate such wastes
• Solid or viscous wastes in amounts that would cause obstruction to flow in sewers or otherwise interfere with the proper operation of the treatment works
• Wastes at a flow rate and/or pollutant discharge rate that is excessive over relatively short time periods so that there is a treatment process upset and subsequent loss of treatment efficiency

15.4 SYLMAR, CALIFORNIA – TUNNEL DISASTER, 1971

A disastrous gas explosion in a tunnel under Los Angeles in 1971 took the lives of 17 workers in a Metropolitan Water District tunnel beneath Sylmar, California. Construction was halted for two years while the owner, the contractor and OSHA decided how to resume work and proceed safely. Many warning signs preceded the event but were not fully acknowledged or addressed. A criminal trial for negligence and new California Tunnel Safety Orders (TSOs) resulted in more strict tunnelling procedures. Tunnelling in areas where hydrocarbons are present require special precautions and special procedures as articulated in the TSOs.

The Los Angeles Times (newspaper) reported on 25 Jun 71, Los Angeles Times:

A pocket of natural gas exploded with an earth-shaking roar early Thursday in the midst of a crew of workers drilling a Metropolitan Water District tunnel 250 feet beneath Sylmar. The explosion was the second in two days at the MWD's San Fernando Tunnel, which will take the State Water Project flow from near Sylmar to a covered aqueduct line 5.5 miles away. Both explosions were blamed on methane, the natural gas found in oil fields. Four men were injured in the blast Wednesday. One of them was treated, went back to work, and died in Thursday's explosion.

The tunnel is being constructed by Lockheed Shipbuilding and Construction Co., a Seattle-based subsidiary of Lockheed Aircraft Corporation. The explosion turned the 21-foot-high tunnel into an inferno of blazing gases. The impact of the blast raced toward the tunnel portal.

Six hundred feet from the face of the tunnel, Louis Renteria, 51, was working at a switch on the narrow-gauge rail line. The blast hurled him to the tunnel floor, knocking him unconscious.

Ralph Brissette, 33, of Pacoima, who had been loading slag onto cars at the rear of the work area, was knocked down, but was able to stagger, semi-conscious, toward the east portal more than four miles away.

One thousand feet from the explosion, Paul (Dutch) Badgley, 63, a veteran of 45 years in mines, was blown from the small yellow transporter, an electric locomotive for the cars which remove slag. He staggered to his feet. It was, he said later, a blast "like a heavy dynamite explosion."

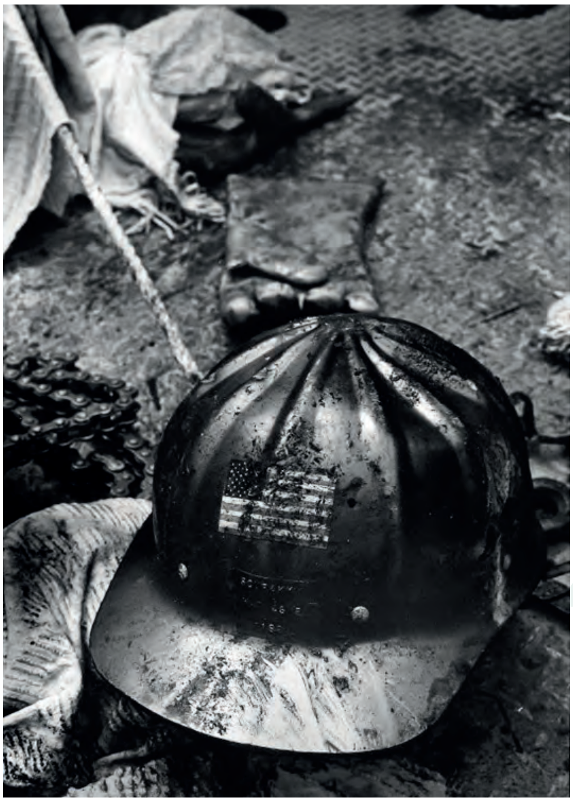
From down the tunnel he could hear the screams of the men trying to escape the holocaust. He jammed his motor in gear and drove toward the trapped and dying men through darkness so thick he could see only inches.

Six hundred feet from the tunnel's end, he found Renteria staggering in the smoky darkness. He took Renteria to safety. Three more times, Badgley, without oxygen, tried to fight his way down the tunnel. The second time he could still hear men crying for help. He backed-out until he could get a breath of air and tried again. This time, and the last time, he heard no sound.

Other rescuers, with fresh oxygen, made their way into the tunnel. It was, said Fire Department Division Chief Robert Radke, "a raging inferno – everything burning, pieces falling from the ceiling, smoke so thick you couldn't see your hand before your face." Two Lockheed workers, John Wallace and John Rathbun, were 300 feet from the site of the blast and nearly running out of oxygen with they heard a shout: "Help."

In the darkness they found Brissette. They put him on a car and headed for the Gate Shaft. The steel basket lowered by the crane was waiting at the bottom of the shaft. Brissette was lifted from the concrete-lined opening, placed in an ambulance, barely conscious, and taken to Tacoma Lutheran Hospital. He responded quickly to emergency treatment for shock and smoke inhalation.

The Lockheed Shipbuilding and Construction Company faced charges on negligence and safety violations stemming from the Sylmar tunnel explosion. Judge George Trammell III ordered a film made after ruling a tour of the tunnel was too dangerous for the jury. The trial lasted 54 weeks. The July 28, 1973, Los Angeles Times reported, "Lockheed was found guilty of 16 counts of gross negligence and 10 counts of violations of state industrial safety code."



15.5 GLOSSARY OF TERMS

Accelerator
A substance added to concrete/shotcrete to accelerate setting.

Adit
A tunnel driven from ground surface to provide access to or drainage from underground workings; a length of tunnel driven for an exploration – exploration adit.

Advance
The forward progress in the construction of a tunnel, usually measured by the length created, or the rate of segment positioning in terms of a number per hour/day or some other timescale.

Backfill
A material used to replace excavated soil.

Bentonite
Bentonite is clay composed, like fuller's earth, mainly of the same clay mineral 'montmorillonite'. It is used for synthetic reasons, expanding properties when water content increases.

Bore
The internal diameter of a pipe or other cylinder, single tunnel; e.g. Twin Bore.

Borehole
A hole driven into the ground to get information about the strata, or to release water pressure by vertical sand drains, or to obtain water, oil, gas, salt etc.

Boring / Bored
Making a hole in the ground by means of a rotating auger.

Box Jack / Jacked Box
A fully built structure that is constructed and then thrust into final position from an adjacent jacking point.

Caisson
A foundation constructed at surface and sunk to its final position. Caissons can have solid or open bases depending on the ground they are being sunk into (generally open caissons are sunk into softer ground; e.g. clay). Caissons can also be filled with compressed air, which provides dry working conditions when using an open-base caisson.

Canopy Tube
A metal tube drilled into the tunnel face above the ground to be excavated, the tubes are pumped full of grout once in place. A series of tubes are drilled forming a 'pipe umbrella'. This umbrella helps poor ground to arch over the tunnel, reducing the risk of crown failure.

Compressed Air
It is used during excavation to apply pressure to the face and prevent the face coming in. Also, to prevent water influx and keep the excavation dry. This method carries health and safety implications as it involves miners working in pressurized air conditions. Used to gain access to face when using enclosed face TBM in certain eradiation.

Compensation Grouting
A method of reversing ground settlements by injecting grout into the ground. The volume of grout must be carefully controlled in order to prevent heave whilst eliminating settlement.

Conveyor
Used in tunnelling to remove excavated material from a tunnel face or shaft. The conveyor takes the material from the face to the tunnel spoil handling point, where it is dealt with.

Cross-Passage
A small tunnel used to connect between adjacent bores in a multiple-bore tunnel. Cross passages provide a means of escape from an incident bore and allow equipment to be placed out of the main bores. It also provides access for Operations and Maintenance.

Crown
The highest point of the internal curved surface of a tunnel cross section.

Cutterhead
The head at the front of a tunnel boring machine used for cutting into the ground. Cutterheads have different designs depending on the type of ground they are built to operate in. Hard rock conditions are tackled by installing cutting discs which shear the rock off the face. Softer conditions require picks to be fitted to the face, these scoop away the ground.

Cut and Cover Tunnel
A method of tunnel construction involving excavating a trench, installing the structure and covering it over. This method is typically used for shallow tunnels. Great care is required to ensure the walls of the excavation are well supported while the structure is installed.

Dewatering
The removal of water from granular soils, it is normally carried out within an impermeable cut-off wall and by using well points.

Diaphragm Walls
A concrete retaining wall (usually reinforced) which is constructed in panels from the ground surface. Excavation for panels is undertaken by a long-arm excavator, with the ground supported by bentonite mud or similar. Once the reinforcement cage has been lowered into place, concrete is poured into the slot, displacing the mud. Once all panels have been cast, excavation of the ground within may proceed.

Double Shield
A tunnel boring machine that is formed of two sections, each being capable of independent forward movement, this allows concurrent excavation and building of a tunnel lining.

EPB (Earth Pressure Balance Machine)
A type of tunnel boring machine which retains a prescribed amount of excavated soil in the cutter head. Hydraulic jacks are used to force this soil against the face of the tunnel, ensuring the ground remains stable. Normally used in granular soils.

Extrados
The outside face of a structural element: i.e. the tunnel extrados.

Extensometer (inclinometer)
A device for measuring the change in distance between two points. Often used for measuring the ground movement induced by tunnelling.

Expanded Lining
Primary lining that consists of tunnel segments that are expanded circumferentially against the surrounding ground.

Eye (tunnel eye)
The start of a tunnel, normally at a junction between a shaft and a tunnel.

Face Loss
The loss of material from the face of a tunnel.

Fault
A break in the bedding of rocks, it displaces any deposit vertically by the 'throw' and horizontally by the 'heave' or lateral shift.

Fibre (reinforced)
Steel fibres of 0.1 – 1.0mm thickness, up to 60mm long, which are used to reinforce concrete, particularly sprayed concrete. FRC can provide superior fire protection and crack control.

Floatation
The buoyancy of a void (e.g. tunnel) beneath the water table.

Forepoling
A system of placing "fore poles" into the ground ahead of the tunnel face to provide a canopy under which excavation can take place.

Framing/Frame
Support around an opening, i.e. forming a portal for cross passage excavation.

Freezing (ground treatment)/Ground Freezing
The process of freezing the ground to enable safe excavation of water bearing deposits.

Geotechnical Engineering
A branch of civil engineering concerned with the engineering behavior of the ground.

Ground Freezing
A technique used to control groundwater and support excavations, where coolant is circulated through tubes inserted into the ground in order to turn any water in the ground into ice.

Grout
A construction material, usually composed of water, sand and cement, but also a large number of other materials, used to improve ground conditions, fill voids in the ground or embed reinforcing bars. Fill the annulus around tunnel segments to hold the shape of the ring.

Grout Hole
A small diameter hole in a tunnel lining to allow grouting up of any voids behind the tunnel lining.

Heading
The top section of a staged mined tunnel excavation, normally excavated first, followed behind by the bench and invert.

Headrace Tunnel
A tunnel carrying water under pressure from a reservoir down to the turbine hall of a hydroelectric power plant.

Heave
The movement of the base of excavation, or tunnel invert upwards, caused by the removal of confining pressure of the ground.

Hydrophilic
A material which expands on contact with water. Hydrophilic gaskets are used on tunnel segment joints.

Immersed Tube Tunnel
A tunnel assembled under water from preformed structural units, usually floated into position and sunk onto prepared foundations.

Inclinometer (Extensometer)
An instrument used for measuring angles of slope (or tilt), elevation or inclination of an object with respect to gravity.

Intrados
The inside surface of a tunnel.

Invert
The bottom surface of a tunnel.

Jet-Grouting
Grouting of the Earth, done under pressure, to stabilize the ground.

Lagging
Heavy planting made to construct walls in excavations and braced cuts.

Lattice Girder
A lightweight curved steel structure installed at the exposed face used to ensure the correct tunnel profile is achieved and also to carry any canopy support (canopy tubes or spiles).

Mesh
Steel bars in a lattice structure which enables shotcrete/fire resistance concrete to bond to the tunnel lining.

Mined Tunnel
This is excavated rather than immersed or cut-and-covered by means of drill &blast, TBM, road-header or hand-mining.

Monitoring
Quantified assessment of a tunnel's infrastructure movement; e.g. tunnel structure itself, any rails, any electrical equipment or the tunnel's environment e.g. temperature and pressure.

NATM
New Austrian Tunnelling Method is a philosophy of excavating tunnels in rock. It is based on 7 principles – mobilisation of the strength of rock mass, shotcrete protection, monitoring, flexible support, closing of invert, contractual arrangements to allow for changes in support and construction method during construction, and rock mass classification.

Niches
An area/adit off the main tunnel used for emergency supplies – fire extinguishers, fire hoses, telephones etc.

Over-Break / Over-Excavation
This is a larger tunnel diameter than required due to poor rock or soil breaking away into the excavation.

Parallel Cut (blasting)
Method of excavating a tunnel from the working face. A central hole is drilled while parallel holes are drilled and charged. The central hole provides the space used when the other filled holes explode, controlling the direction of the energy dissipation.

Pilot Tunnel
A smaller diameter tunnel bored for investigative purposes before the main tunnel drive. It can be expanded into the final tunnel cross section, for example for the Uetliberg Tunnel in Switzerland a 5.00m pilot tunnel was excavated with a tunnel boring machine and then enlarged to the final cross-section of 14.20m wide by 14.40m high by a tunnel bore extender (TBE) employing undercutting.

Pipe Jacking
A method for directly installing pipes behind a shield machine by hydraulic or other jacking, from a drive shaft such that the pipes form a continuous string in the ground.

Piping
Internal erosion that leads to sudden collapse.

Plug (shaft)
A thick concrete base of a shaft, that is heavy enough to prevent uplift and flotation for the whole structure.

Polypropylene Fibre Reinforced Concrete
Concrete made with fine polypropylene fibres included in the mix, either used as a sprayed lining or in precast segments. The fibres' main purpose is to improve the performance of concrete at high temperatures, as may be experienced in a tunnel fire. The fibres melt leaving cavities in the concrete which can be used by released water vapour reducing explosive spalling of the lining.

Portal
Entrance, or structure that forms the entrance, to a tunnel.

Precast (concrete)
Uniform units of concrete cast away from the site where they are to be used, more complex shapes can be created to higher tolerances than cast in situ equivalents. Installation on site is greatly simplified and avoids the need for storing composite ingredients of concrete and handling cement materials, for example Beany Drainage in line kerb units and tunnel linings/segments.

Primary Lining
Structural tunnel lining that is placed against the ground.

Rib
Circular or arch support (usually steel I beams) used to support/strengthen excavations, often used in conjunction with timber boards (ribs and logging).

Ring (number, closure, closure distance)
Pre-cast concrete segmental lining of finite length.

Ring Beam
This is a ring-shaped structural member usually carrying bending/vertical gravitational loads.

RMR – (Rock Mass Rating)
The sum of six rock quality parameters (uniaxial compressive strength of rock material, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions and orientation of discontinuities). Scale 0 to 100.

Roadheader
Excavating equipment consisting of a boom-mounted cutting head, a loading device usually involving a conveyor, and a crawler travelling track to move the entire machine forward into the rock face. Similar to a profiler.

Rock
Materials consisting of the aggregate of minerals, like those making up the Earth's crust that has not been broken down into loose material.

Rock Arch
This is the phenomenon of rock around an underground excavation behaving as an arch, transferring compressive loads to either side of the excavation. A self-supporting excavation shape where the rock is broken to form a natural and stable arch.

Rock Bolt
This a long bolt for stabilising rock excavations by transferring loads into the confined strong rock interior.

Q system (Tunnel Quality Index)
This is a widely adopted system proposed by Barton et al in 1974 for the determination of rock mass characteristics and tunnel support requirements. Properties, such as blockings, inter-block shear strength and the active stress condition of the rock mass are given numerical values based on tables from case studies. The final numerical value for Q varies on a logarithmic scale from 0.001 to 1000.

Secondary Lining
Lining in addition to primary lining for decoration, improved fluid flow, protection, structural enhancement or other purposes.

Settlement
Downward movement of the ground surface.

Shaft
A shaft is a vertical or steeply inclined excavation used as a passage from the surface to the workings, used for ventilation, travelling, hoisting, or all three. Shafts are usually of limited cross section in relation to their depth.

Shield
A protective tube used in soft ground, inside which a TBM works, the shield eliminates timbering.

Shield Driven
Method of excavation in the front of a tunnel or pipe jack using a shield. (see shield)

Shotcrete
A commonly used term for mortar or concrete sprayed through a hose and

pneumatically projected at high velocity onto a surface.

Single Pass
A tunnel which only has one layer of lining.

Slurry
A mixture of bentonite and water.

Slurry Shield
Method using a mechanical tunnelling shield with closed face which conditions the ground and employs

Soft Ground
Normally consisting of sands/gravels, extra consideration is required in tunnelling through this material, as soft soils are unstable over a certain period and must be considered as less predictable than hard rock.

Spile
Bars inserted into a tunnel face to act as a form of ground improvement.

Spoil
Earth material from an excavation.

Sprayed Concrete (lining)
SCL is an established method of tunnelling using sprayed concrete to support the excavation both temporarily and permanently (see shotcrete for picture).

Spring Line
This is the point where the curved portion of a tunnel roof meets the top of the wall. In a circular tunnel the spring lines are at the opposite ends of the horizontal centreline.

Squeezing Rock
Difficult tunnelling ground conditions characterised with (usually) the rock being strongly jointed and fractured and having low strength.

Steel Fibre Reinforced Concrete (fibre)
A concrete mix that contains short discrete steel fibres that are uniformly distributed and randomly oriented throughout the mix opposed to conventional steel rebars used in reinforced concrete.

Steel Sets/Arches
Steel support structure for tunnel construction.

Sump
A pit in which water collects before being baled or pumped out.

Tail Skin
A rear end shield forming a tail seal and used for building the segmental rings.

TAM (tube a manchette)
A Manchette tube is a PVC or metal pipe in which rubber sleeves cover holes that are drilled in the pipe at specific intervals. The tubes are inserted into holes that have been bored into the “work area” (soil, rock, concrete, etc.) known as the “grout zone”. Grout is pumped to a packer that has been slid into the tube, seals on the packer force the grout through the holes in the tube, past the flexible rubber sleeve, and into the grout zone to help stabilize and/or seal it.

TBM – (tunnel boring machine)
A machine for excavating circular tunnels, a rotating cutting wheel breaks the ground, which drops through slots in the cutting wheel for removal.

Top Heading
A small tunnel dug ahead of the main excavation, they are dug at the crown of the tunnel. Top headings are used in the top-heading-and-bench method, the main advantage being that engineer can use the heading tunnel to gauge the stability of the rock before moving forward with the project.

Tunnel
An underground passage, open to daylight at both ends. If open only at one end, it is called a drift or an adit. A tunnel is a horizontal or sloping underground enclosed way of some length.

Tunnel Lining
Permanent or temporary cover to the rock or soil surface at the periphery of a tunnel excavation.

Umbrella Tube
Another name for canopy tube, a supportive structure made of multiple tubes bored around the drilling face of a tunnel, which are then filled with cement.

Underground
Adjective which refers to a location beneath natural (or manmade if landscaping has taken place) ground level, as opposed to being at ground level or above ground.

Volume Loss
This is the volume of the settlement trough and is usually expressed as a percentage of the tunnel face area. Volume loss is the result of convergence and face loss (movement of the walls and face of the tunnel respectively) in the tunnel.

Waterproof Membrane
A skin provided external to the immersed tunnel to improve the water tightness of concrete. The membrane may be of steel or other more flexible materials.

Wedge-Block (lining)
The lining used is of an expanded type. The expanded lining or wedge block technique has been developed for impermeable cohesive soils with a stand-up time of several hours (such as the over-consolidated London clay).

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