

HANDLING, TREATMENT AND DISPOSAL OF TUNNEL SPOIL MATERIALS

Working Groups 14 and 15
Underground Construction and the
Environment and Mechanized Tunnelling

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Loading of tunnel muck, Rosten HEPP, Norway. (Photo Ø. Fæhn, Skanska Norge AS)

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1 >> INTRODUCTION

Working Group 15 of ITA, represents ITA's philosophy on **Sustainable Use of the Underground Space**, based on the UN Brundtland Commission's definition on sustainability:

"Development that meets the needs of the present without compromising the ability for future generations to meet their own needs"

The work within the ITA Working Group 15 on Underground Construction and the Environment, might be divided into three categories with focus on

- Environmental **opportunities** by going underground
- Environmental **challenges** by going underground
- Environmental **Guidelines and Recommendations** when going underground

This report on excavated material from tunnels and underground caverns belongs to a set of reports from ITA's Working Group 15 on "Underground Construction and the Environment". It also benefits from the considerable reports and input from Working Group 14 – Mechanized Tunnelling.

The set of reports produced and planned by WG 15 is :

- Environmental and Sustainable Development Reasons for Going Underground (presented and issued in Vancouver 2010)
- Excavated materials (this report)
- Noise and vibrations (under preparation)
- Water related issues
- Architecture and aesthetics

For collection of relevant information on tunnel muck handling, treatment and disposal, a questionnaire was distributed to the member nations. Altogether information from 59 different projects were received, covering USA, Europe, Asia and Australia.

Also, research programs like the DRAGON Project (Reference 1, a joint cooperation between Austria, France, Germany, Switzerland and UK) and the "Re-Muck" program in Italy (Reference 2) on utilization of excavated materials from tunnels, presents innovative methods for eco-compatible and sustainable recycling of tunnel muck. Both programs give immediate evaluation of the rock quality at the excavation face for finding most suitable treatment techniques and strategies for TBM excavation.

In addition, cases from Taiwan (aggregates, earthworks, shore protection and land reclamation) and Australia (Northside Storage Tunnel Project), England (Crossrail Project), Switzerland (Farettes Hydropower Project and the Gotthard Base Tunnel), and Italy (mechanized tunnelling with EPB TBMs) have been selected as examples on opportunities and challenges related to tunnel muck. Table 1 below lists the projects referenced, illustrated or described in detail in the following sections of the report.

1 >> INTRODUCTION

PROJECT	COUNTRY	CONDITIONS		TUNNELLING METHODS			DAM SITE	
		Rock	Soil	D&B	TBM	NATM	Rock	Soil
Brenner Base Tunnel	AT	✓		✓	✓			
Koralm Tunnel	AT	✓	✓		✓			
Semmering Railroad Tunnel	AT	✓	✓	✓	✓	✓		
Northside Storage Tunnels	AU	✓		✓	✓	✓		
Niagara Tunnel Project	CA	✓			✓			
Bosser Tunnel	DE	✓		✓	✓			
Fidler Tunnel	DE	✓		✓	✓			
Gotthard Base Tunnel	CH	✓		✓	✓			
Nant de Drance	CH	✓		✓				
Lötschberg Tunnel	CH	✓		✓	✓			
Les Farettes	CH	✓			✓			
Gavet Tunnels	FR	✓		✓	✓			
St. Jean-de-Maurienne (LTF)	FR+IT	✓		✓	✓			
Crossrail	GB		✓		✓			
A1 Andorra – San Lorenzo Railway	IT		✓		✓			
Bologna Railway Tunnels	IT		✓		✓			
La Maddalena (TELT)	IT	✓		✓	✓			
Follo Line Railway Tunnels	NO	✓		✓	✓			
Førsvatn Earth and Rockfill Dam	NO						✓	
Kjela Hydropower Plant	NO			✓				
OREA Sewer Plant Expansion	NO	✓		✓				
Rosten Hydroelectric Power Project	NO	✓		✓				
Vestfold Railway Line	NO	✓		✓				
Bay Delta Conservation Plan (water)	US		✓		✓			
Brightwater Tunnels (CSO)	US		✓		✓			
NYC Second Avenue Subway	US	✓		✓	✓	✓		
Port of Miami Highway Tunnel	US		✓		✓			
Portland West Side CSO Tunnel	US		✓		✓			
SR 99 Highway Tunnel	US		✓		✓			
Suhua Highway Improvements	TW	✓		✓		✓		
Caopu Highway Tunnel	TW	✓		✓		✓		
Taiwan High Speed Rail						✓		

Table 1: Projects Referenced in the Report - Many projects were referenced, illustrated or described in detail in the report. In many cases, the tunnel muck handling, treatment and disposal was examined and evaluated in comparison to other similar projects.

2 >> ACKNOWLEDGEMENTS

This report presents collective work of the Working Group 15 - Underground and the Environment - of the International Tunnelling and Underground Space Association, ITA with assistance from Working Group 14 – Mechanized Tunnelling. Hereby we would like to acknowledge the Working Group 15 and 14 members, who contributed by discussing the report over the years of preparation and provided inputs, as well as external colleagues, who provided information and critique of the report.

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In addition to the 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, has been of valuable use for preparation of this report.

During the period of the report preparation, the past Animateur of the Working Group, Jan K. G. Rohde, has been the Lead Author. The report was completed by the present Animateur of WG 15, Cédric Thalmann, with valuable assistance and significant contributions from Brian Fulcher, the Animateur of WG 14. A very thorough and helpful Peer Review was completed by Jacques Burdin.

The authors would like to acknowledge help and arrangements made by the Secretariat of the International Tunnelling and Underground Space Association.

3 >> SUMMARY AND INTRODUCTION

Handling, treatment and disposal of tunnel muck is today a fundamental issue in a tunnel project. Considering the potential cost reduction, possible income, and environmental effects of tunnel muck, the proper and environmental sensitive disposal is an essential issue of the Life Cycle Assessment (LCA) of a tunnel project. Used directly in the project, there are both environmental and cost benefits.

However, there is a big difference between hard crystalline rock, soft, anisotropic and soft sedimentary rock and loose soil. Furthermore, the method of excavation, conventional drill and blast, TBM, EPB, roadheader or just excavated loose soil/rock for tunnelling, is also of great importance to the quality and potential treatment(s) and disposal options for tunnel muck.

Besides opportunities, there are challenges and potential conflicts related to excavated material from tunnels and underground caverns. Potential environmental challenges with excavated rock from tunnels and caverns might be related to the rock/soil itself, excavation methods, logistics, handling and transport as well as temporary storing and permanent depositing.

In many countries, the tunnel spoil is defined as waste material, if no applications are possible or no solutions can be provided. National regulations should provide a clear distinction between “waste” materials and products for use from tunnel spoil.

For optimal handling and use of the tunnel muck, it is very important to prepare a Tunnel Muck Management Plan, and the planning should start at an early stage to ensure an efficient process through politicians, stakeholders and decision makers and implemented throughout the entire tunnelling program including shafts, portals and caverns.

In the following chapters, we will follow the tunnel spoil from solid rock and soil to its final destination.

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

Handling, treatment and disposal of tunnel muck is today a fundamental issue in a tunnel project. Considering the potential cost reduction, possible income, and environmental effects of tunnel muck, disposal is an essential issue of the Life Cycle Assessment (LCA) of a tunnel project (References 1 and 4).

There are several opportunities for using excavated material from tunnels and underground caverns. As examples might be mentioned :

- Embankments, foundations and landfill
- Land reclamation
- Earth and rock-fill dams
- Aggregates for concrete and asphalt pavement
- Sub-base, pavement, ballast and superstructure
- Erosion, shore and slope protection
- Masonry walls and gabion
- Rockfall defence
- Construction sites
- Backfill to borrow areas and landscape rehabilitation

Opportunities to utilize the excavated materials from tunnels and rock caverns, depend on the quality of the rock itself as well as the excavation method, handling and transport (See Figures 1 and 2).

There are big varieties in the geology and rock types from project to project. From hard crystalline igneous or metamorphic rock to soft or loose sedimentary rock, the potential use might be large, limited or none.

There is also a big difference between excavated rock from conventional drill and blast, TBM (Tunnel Boring Machine), EPB (Earth Pressure Balanced machine), or just excavated material from cut and cover tunnels and soft rock tunnelling without using explosives (Figures 3 and 4).

A good example of tunnel muck use is the Gotthard Base Tunnel producing more than 14,000,000 m³ of solid rock (Figures 5 to 8). During the Gotthard Base Tunnel case study, the focus has been to use most of the excavated material, economically



Figures 1 and 2 : Left - Tunnel muck is a valuable resource (photo Ø.Fæhn, Skanska Norge AS). Right - Material depot and gravel plant for the aggregate production in Sigirino (photo Ø AlpTransit Ceneri)



Figures 3 and 4 : There is a big difference between tunnel muck from conventionally driven hard rock tunnel at Rost en HEPP, Norway (photo Ø.Fæhn, Skanska Norge AS) to soft rock tunnels excavated by backhoe excavators at the Taiwan Highspeed Rail, Taiwan (photo J. Rohde, Sweco Norge AS).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

optimize the management of the material and to minimize the environmental impact. The following issues have been essential :

- Aggregate for concrete to be obtained from their own sites
- Transport and intermediate storage to be of low emission type
- Noise and dust emissions to comply with legal limits

At the Gotthard Base tunnel, approximately the following break-down and distribution was achieved.

- 20% of the tunnel muck was used for embankments related to the project (Figure 9)
- 32% as aggregate for concrete production including lining segments
- 44% sold to third parties for environmental restoration (ex. building of islands).

At this project, cost for tests and plant facilities was estimated to be 8 million Swiss Francs, while savings due to lower costs for purchasing sands and gravel, and transport cost reduction are estimated to 100 million Swiss Francs (Reference 5).

At the 57km railway tunnel between St. Jean-de-Maurienne (France) and Susa (Italy) (Railway Lyon – Turin) 32 million tons of tunnel muck will be produced. In the project, management on handling and use of tunnel muck are in focus to minimize environmental impact, which is basic issues of the sustainable policy. Approximately 28% of the excavated material is expected to be used as concrete aggregates for tunnel lining. Altogether 5 million m³ concrete is expected to be produced. However, geological formations with too high sulphate content is also identified, requiring management and valorisation of the tunnel spoil. Therefore, handling of excavated materials become one of the basic issues for sustainable development policy in order to minimize environmental impacts by limiting transport, final storage or external material contributions (Reference 6).

Another interesting project is the Follo Line Railway in Norway (Reference 7), 20km double tube tunnel which is under construction (Figure 9). Most of the tunnel (~18km) are constructed by TBM and



Figures 5 to 8 : Spoil management areas: top left: Ceneri (photo Ø AlpTransit Ceneri), top right: Bodio (photo Cédric Thalmann), bottom left: Amsteg (photo Ø AlpTransit Gotthard); Bottom right: Faido (photo Ø AlpTransit Gotthard)

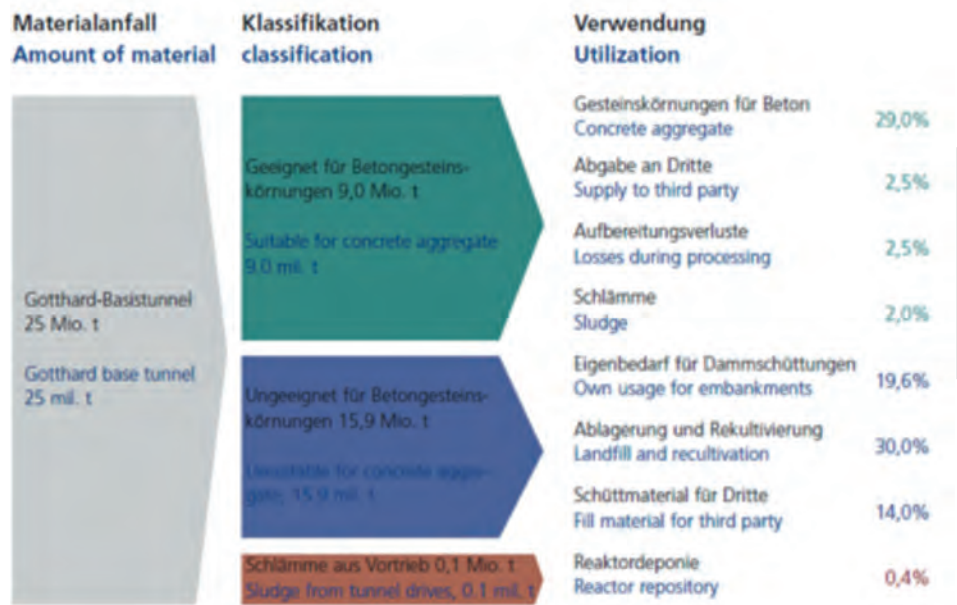


Figure 9 : Utilization of muck for the Gotthard Base tunnel (Reference 3)

~2km by conventional drill and blast methods, producing altogether 9 million tons of rock. The tunnels are constructed in Precambrian gneiss, and a construction plant is established in the abandoned quarry at Åsland, where the tunnel muck was planned to be used for tunnel segment and concrete production (Figures 10 and 11). Approximately one-third of the rock material is used for preparation of a future

township for the increasing population around Oslo. Additionally, approximately 10 to 15% of the material was planned to be used for production of 141,000 tunnel lining segments and other concrete structures.

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

Unfortunately, through tests during construction, the mineral Phyrrotite was discovered in approximately 20% of the samples from the tunnel spoil. This, in combination with more than 0.1% sulphate content, resulted in disqualification of the TBM spoil as concrete aggregate.

The use as landfill for the future township is however in progress, and the procedure of testing and compaction is followed closely by supervision on site. The following tests are conducted for each compacted layer of TBM muck :

- Troxler test
- Grain Size Distribution tests (in laboratory)
- Plate load test
- Standard Proctor Compaction test

In addition to the test program conducted for each layer, a total of five shaft tests and lidar scanning on monthly basis are performed.

Some examples of actual projects with indication of the geology and percentage of use of the muck are given in Table 2 (Reference 1).

At the Delta Bay Conservation Plan in USA (References 8, 9 and 10), material use plans are prepared for reusable tunnel and dredged material of a delta area. Focus in the project has been to obtain the “Best Management Practices” for the Material Use Plan, containing for example the following;

- Maximal distance from construction feature to material storage (maximum 10 miles)
- Minimum distance to existing residential or commercial buildings (minimum 100 feet)
- Placement of material in sensitive natural communities and habitat areas to be avoided or minimized to the extent feasible, not to be placed within 250 feet of vernal pools or alkali seasonable wetlands
- Landowners concerns and preferences to be considered
- Refine the storage areas footprint to further minimize impacts to surrounding land uses
- Proposed locations of storage areas for reusable tunnel material to be designed to be close to where the material will be brought to the surface, as well as close to where use is expected to occur
- Chemical characterization of dumped material, additives to be used for tunnelling to be non-toxic and biodegradable



Figure 10 : Aerial view from the Åsland construction plant at the Follo Line Railway Tunnel showing conveyor belt, sorting plant and concrete lining segment factory.



Figure 11 : High strength precast concrete tunnel lining segments.

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

COUNTRY	PROJECT	EXMAT DESCRIPTION			TUNNEL MUCK END USE	
		(kt)	Type	%	Material	Portion (%)
Austria	Semmering	12,800	Albitegneiss	34	Concrete and Aggregates and Embankment	Study Phase
			Amphibolite	10		
			Dolomite and marble	13		
			Phyllitic schist	10	Landfill	
			Micashale + Phyllitic Material	33		
Germany	Fidler Tunnel	4,700	Siltstone + Clay	20		
			Gypsum and Anhydrite	40	Plaster	
			Sandstone + Marl	25		
			Sandstone + Limestone	15	Concrete aggregates	
	Bossler Tunnel	4,700	Opalineousstone	40	Bricks	
			Sandstone	35	Silica bricks	
			Sandstone + Siltstone	20	Cement	
France	LTF Maurienne Ambin Base Tunnel	31,000		5		
			Quartzite	3	Concrete aggregates and embankment	
			Limestone	2		
			Gneiss + Micashale	22		
			Sandstone	18		
			Permian Micashale	22	Landfill	
			Gypsum + Anhydrite	6	Cement	
Italy	LTF La Maddalena	600	Shale, Carbon	21	Landfill	
			Paragneiss	27	Landfill	
France	Gavet	650	Micashale	63	Concrete aggregate	
			Amphibole	95	Road pavement and aggregates	
			Gneiss			
Switzerland	Les Farettes	135	Leptynite	5	Landfill	
			Limestone	75	Concrete aggregates	
United Kingdom	Crossrail	6,000	Marly limestone	25	Landfill	
			Clay	20	Landfill	
			Marls	45		
Switzerland	Nant de Drance	4,600	Sand and Gravel	35		
			Granite	22	Concrete aggregates	
			Gneiss			
			Micashale	78	Landfill	
Austria	Koraln Tunnel	14,800	Metagrawacke			
			Gneiss/Schiefergneiss	35	Concrete aggregates embankment and outside use	
			Amphibolite	3		
			Marble	5		
			Micashale	25		
			Sandstone/Schlufstein	32	Landfill	

Table 2 : Examples of Actual Projects with EXMAT Material Quantities
Sample summary of recent tunnel projects with the geological distribution noted along with tunnel muck handling, treatment and final disposal options realized (Reference 1)

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

The following sections of the report describe some potential use of excavated rock material from tunnels and underground caverns.

4.1. TEMPORARY CONSTRUCTION PURPOSES

In most tunnelling and underground projects, there will be an immediate need for the contractor to establish stable foundations for the construction plant, construction and maintenance of access roads and operational areas within the construction plant (Figure 12). For most rock types, excavated rock from tunnels and rock caverns might be used for this purpose. A problem is that the need of excavated material is immediate and comes even before the tunnel excavation has started. This fact must be considered during planning.

Depending on the rock quality, the tunnel rock masses will in most cases be useful for temporary construction purposes during the construction stage, also for temporary road pavement in the tunnels themselves.

4.2. EMBANKMENTS, LANDFILL AND EROSION PROTECTION

Embankments and landfill are maybe the most feasible and cost-effective way of utilizing excavated rock from tunnels and rock caverns. Used in the project itself gives short transport distance, reducing the CO₂ footprint (Figure 13).

Common use of tunnel muck is embankments for roads and railways, earth and rockfill dams, improvement of foundations for housing and industrial areas, land reclamation etc. The quality, gradation and composition of the excavated rock is often of such quality that it can be used directly without any processing.

Excavated materials from drill and blast tunnels can also be used for slope stabilization as well as flood and erosion protection along rivers and seashores. For these purposes, separation or crushing might be required to some extent.



Figure 12 : Temporary access road. Follo Line Railway Tunnel Project, Norway (Bjørnar Gammelsæter 2015).

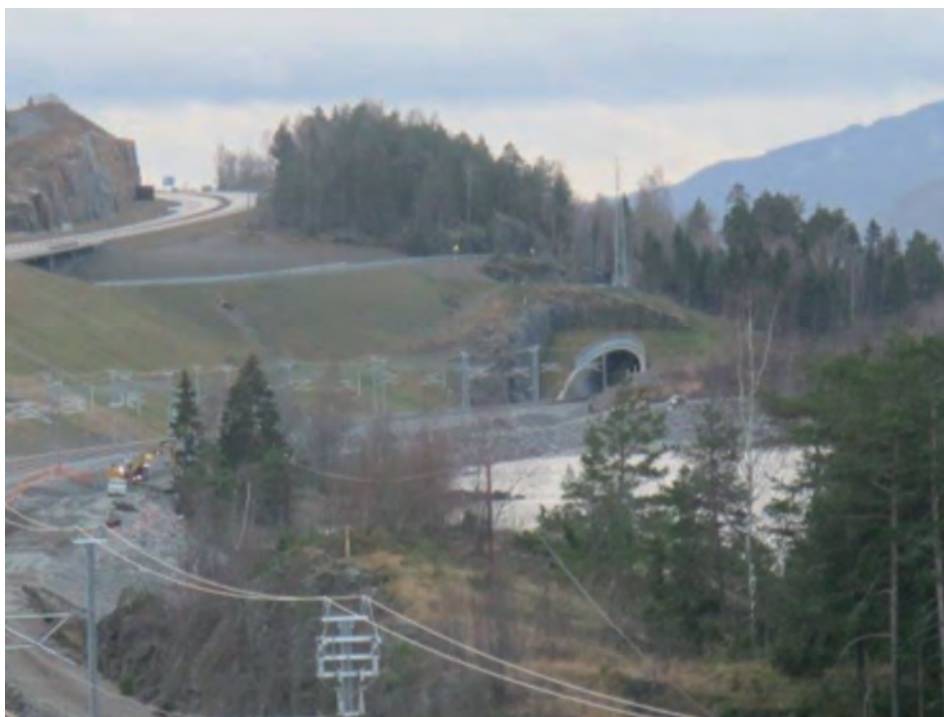


Figure 13 : The Joint Venture Project HighwayE6/Double Track Railway along Lake Mjøsa, Norway. (Sjur Krogstie, Norwegian Public Road Administration/NPRA 2015).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

Excavated rock from tunnels are excellent as material for wave protection along sea shores. An example is shown in Figure 14, where wave breakers are made from large rock pieces from road excavation along the road to the outermost point in Lofoten, Norway. In this case, tunnel spoil was unfortunately considered to be too small. In Taiwan, however, tunnel spoil is utilized as shore protection along the east coast to protect the shore against erosion from regular and aggressive typhoons along the east coast (see Sections 8.1.1 and 8.2.2).

4.3. EARTH AND ROCK FILL DAMS

Earth and rockfill dams are constructed to create reservoirs or to increase the volume in natural lakes, and thus to increase the reservoir volume for water supply and/or hydropower production. Normally, a system of tunnels is constructed as part of the hydropower or water supply schemes, and excavated material from the tunnels might have a very good potential for use in these dams.

4.3.1. Førsvatn Earth and Rockfill Dam, Norway

One example is the Førsvatn Dam, Telemark, Norway, a part of the Tokkel V Hydropower Project (cross-section Figures 15 and 16).

The Førsvatn dam was constructed in the period from 1976 to 1979 when there was a great development of hydropower plants in Norway. For construction of the dam, the following materials were used:

- 1a and 1b : Core of moraine/till
- 2a and 2b : Gravel filter from river deposits, 2b partly crushed tunnel spoil 0 to 90mm (2b downstream of the core)
- 3 : Transition zone from tunnel spoil
- 4 : Rock fill from open quarry
- 5 : Rip rap/ slope protection from open quarry
- 6 : Dam crest from open quarry
- 7 : Drain toe, large boulders from open quarry

Bedrock in the area is mainly various gneisses of Precambrian age. Overview of the dam from the construction period is shown in Figure 15.



Figure 14 : From Lofoten, Norway, with heavy storms from the Norwegian sea. Large boulders from blasted rock are used as wave breakers in subsea embankment up to 3m below sea level along the shore for erosion protection.

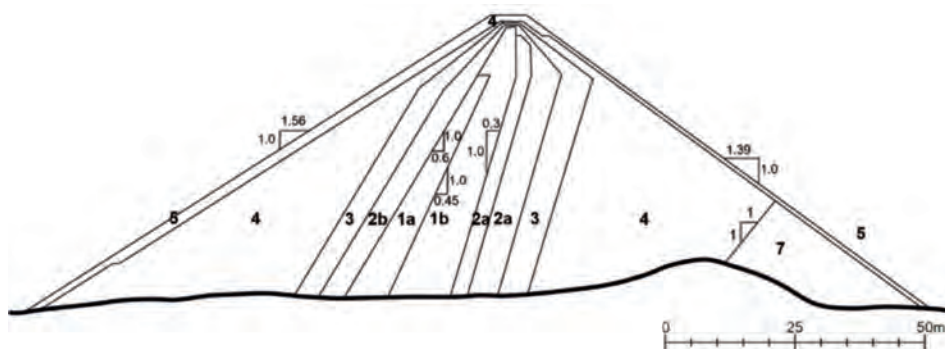


Figure 15 : Cross section of the Førsvatn earth and rockfill dam, Kjela Hydropower Plant, Telemark, Norway (Statkraft/NGI).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

A total volume of tunnel spoil used in the dam body was approximately 100,000 m³ compacted fill whereof approximately 24,000 m³ as crushed rock in Zone 2b downstream and 86,000 m³ in Zone 3. The volume of Zones 4, 5, 6 and 7 was 431.000 m³ compacted rockfill and rip rap, while the total volume of the dam was approximately 721,000 m³.

Grain size distribution curves from tunnels and rock caverns are presented in Figures No. 17, 18 and 19 (filter 2b, crushed), 3 (Zone 3 transition, tunnels) and 4 (Zone 4, rockfill, quarry/bench blasting).

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Grain size distribution curves from tunnels and rock caverns are presented in Figures N°. 17, 18 and 19 (filter 2b, crushed), 3 (Zone 3 transition, tunnels) and 4 (Zone 4, rockfill, quarry/bench blasting).

4.3.2. Some Comments to Blasted Tunnel Spoil

Besides geology and rock type, the Grain Size Distribution (GSD) curves of excavated rock from conventional drill and blast tunnels depend both on the tunnel cross section, borehole diameter and drill pattern as well as the unit charge (kilogram explosives per cubic meter). Furthermore, the GSD curves might change due to handling and transport, since the rock is influenced by the explosion, and hence cracked. Tunnel muck has also sharp edges that will be cracked and crushed during loading, dumping, dozing and compaction, producing more fines.

The GSD curves in Figure 20 are from transition zones in some Norwegian rockfill dams after compaction (Statkraft/NGI). Furthermore, the largest rock pieces are removed to satisfy the filter and compaction criteria. The tunnel spoil is from tunnels with cross-sections between 8 and 20m². Larger tunnel cross-sections (road and railway tunnels) will generally produce coarser GSD curves.



Figure 16 : Construction of the Førsvatn Dam 1976-1979 (J. Rohde 1977).

4.3.3. Studies for Utilizing Crushed Rock as Impervious Core

In 1977 studies were carried out at the Technical University of Norway, Trondheim (NTH, now NTNU) (Reference 11), on utilizing crushed rock for the impervious core in rockfill dams. The feasibility of this

concept depends on availability of natural sources or alternatively use of asphalt core in the dam. So far, production of impervious core in dams from hard rock tunnels is not been found to be feasible. For production of asphalt core, crushed rock might be used as aggregate and filter material.

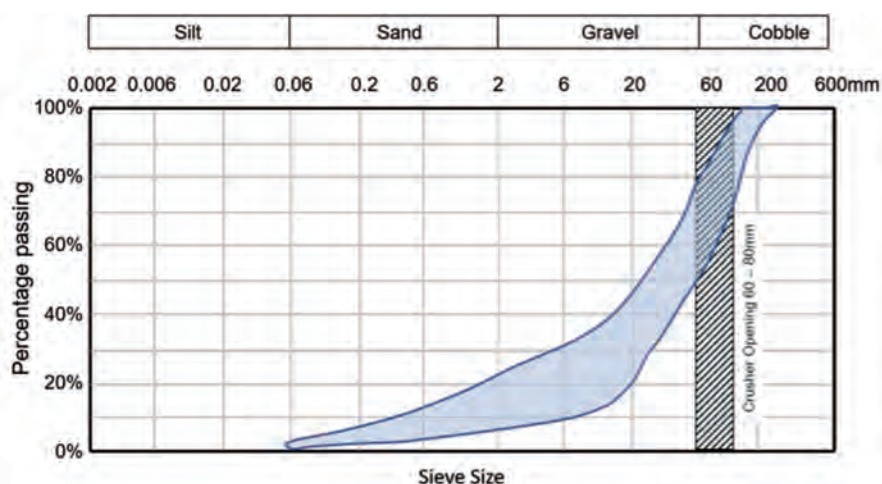


Figure 17 : Grain size distribution curves of Zone 2b filter made of crushed rock. (Kjela Hydropower Plant, Norway, J. Rohde 1978).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

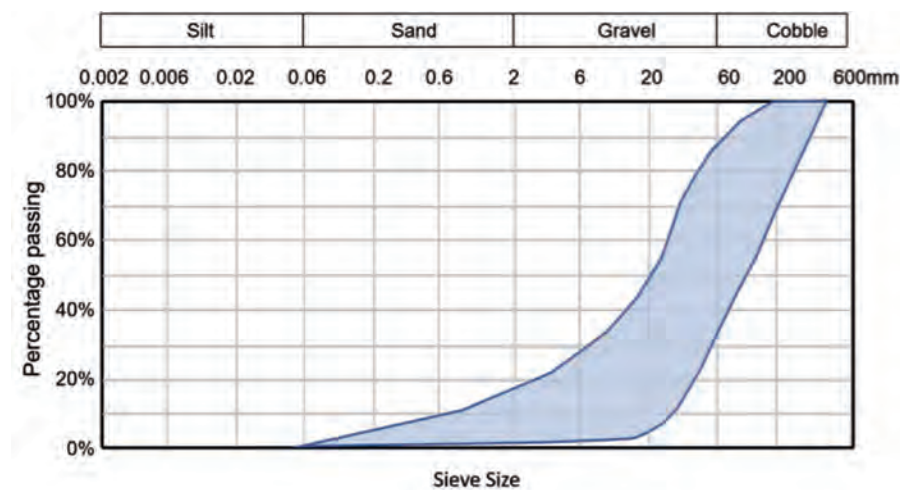


Figure 18 : Grain size distribution curves of Zone 3 transition zone of tunnel spoil. (Kjela Hydropower Plant, Norway, J. Rohde 1978).

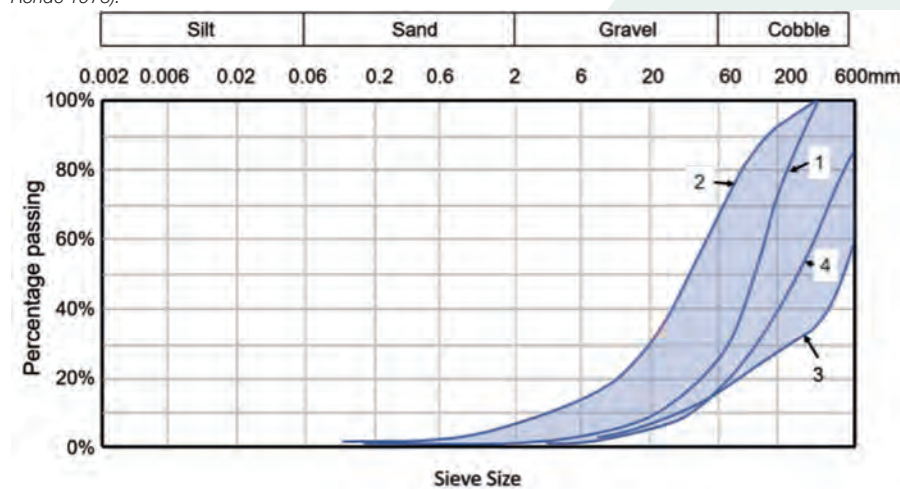


Figure 19 : Grain Size Distribution curves of Zone 4 rockfill from open quarry and bench blasting of the hydropower rock cavern (Kjela Hydropower Plant, Norway, J. Rohde 1978).

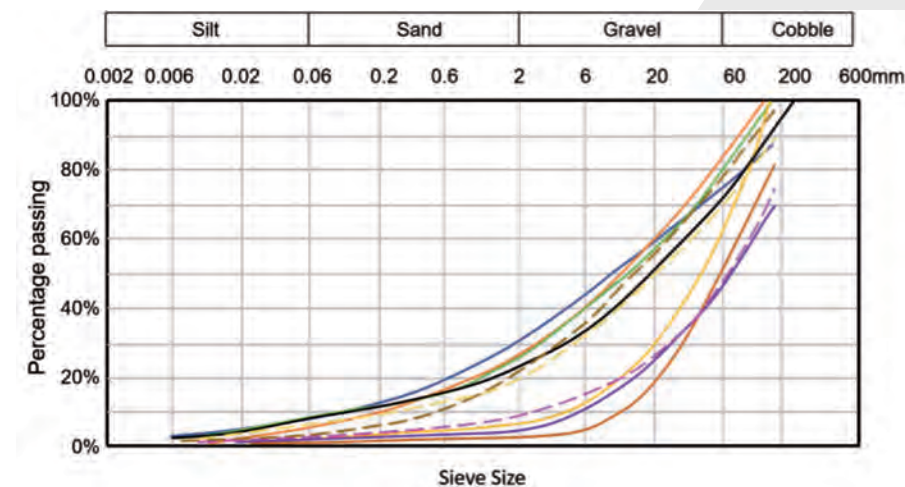


Figure 20 : Grain Size Distribution (GSD) curves from some Norwegian rockfill dams. Large boulders are removed, and the samples have been through compaction.

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4.4. TUNNEL SPOIL FROM TBM ROCK TUNNELS

Due to the way of excavation, there is a great difference between the GSD curves of excavated materials from conventional drill and blast tunnels and mechanized tunnelling.

Tunnel muck obtained from TBM tunnels has smaller size than muck from blasted tunnels and is characterized by a typical elongated and flattened shape. The produced material from TBM tunnels, can be divided into four groups (Reference 4) :

- Rock dust, generated in the contact zone between the discs and the rock
- Splinters and Rock fragments caused by the cutting and detachment of small rock components
- Flakes or chips caused by the cutting and detachment of rock fragments between two adjacent tools
- Blocks generated by the detachment of large pieces of rock because of presence of separation of surfaces in the rock (natural joints)

A very large diameter tunnel in Niagara Falls Canada, produced muck that was originally intended to supply the local brick manufacturing industry. Please refer to Figures 21 to 24.



Figure 21 : Niagara Tunnel Project - General arrangement (source OPG).



Figure 22 : Break-through of TBM (Robbins) at the Niagara Tunnel Project, Niagara Falls, Ontario, Canada. (photo from Robbins).



Figure 23 : Niagara Tunnel Project – Rock Conditions. View of freshly cut tunnel wall showing the degradation, strata and high clay content. (photo from B. Fulcher).



Figure 24 : Niagara Tunnel Project – Rock Conditions. View of freshly cut tunnel wall showing the degradation, strata and high clay content. (photo from B. Fulcher).

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Typical GSD-curves from TBM tunnels are presented in Figures 25 and 26. Grain size distribution curves, also from TBM excavated tunnels, show well grained GSD curves.

Besides the parent rock type, GSD curves of excavated material from TBM tunnels are influenced by several parameters like thrust force and distance between cutter discs. Increase in thrust force creates greater depth of cut, which again creates increased size and more uniform size distribution of muck (Reference 12). Cutter disk spacing > 100mm gives improved excavation efficiency and twice the amount of material with size larger than 32mm compared to normal spacing of 70 to 90mm. Optimal spacing between adjacent tools also gives energy savings. The GSD curves in Figure 25 shows the trend from 1980 TBM machine specifications towards 1995 specifications. The increase in grain size does also reflect improved efficiency.

Grain size distributions from different TBM tunnels in different geologies are shown in Figures 26 to 28 with additional discussions to follow.

Figure 27 shows the of the grain size distribution of a TBM (Herrenknecht 10m diameter) in hard gneiss after crushed in a primary crusher (grain size maximum 150 mm).

Figure 28 shows GSD curve envelope from 19 different TBM tunnels in Norway. GSD curves from the Gotthard Base TBM tunnel is shown with blue lines.

Studies from the AlpTransit project and Aica exploratory tunnel of the Brenner Base Tunnel show, that for TBM tunnels, granules greater than 8mm are generally too flat and not cubic enough while granules less than 8mm have necessary geometrical requirements for concrete aggregate use (Reference 4).

Compared to conventional drill and blast tunnels, material from TBM excavation could have a bad shape and could be more difficult to use. The tunnel spoils that are produced trend to be more elongated and form parallel planes during concreting phase (Figure 29). In that case, the aggregates could trap more water, causing degradation of final structure. It is definitely advisable to avoid poor quality aggregate by using a special type of crusher, such as a Vertical Shaft Impactor.

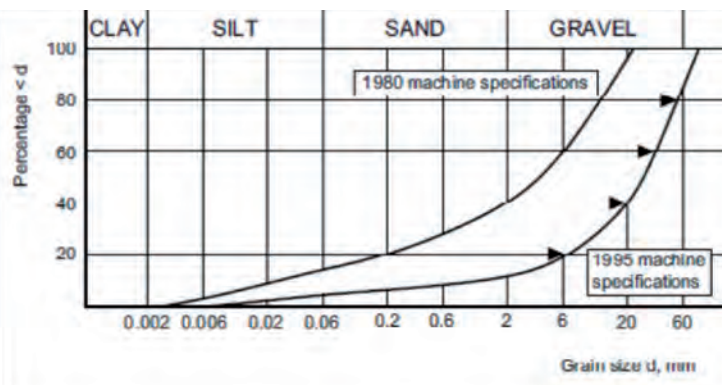


Figure 25 : Typical Grain Size Distribution curve from TBM tunnels.

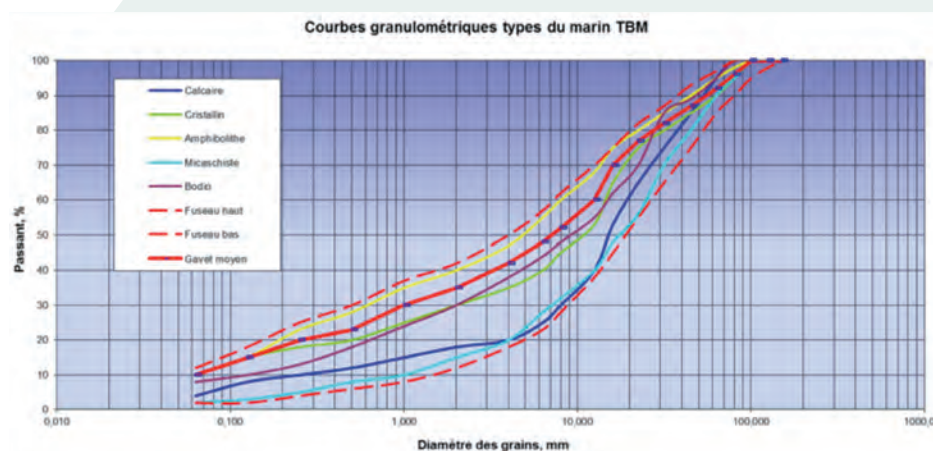


Figure 26 : Typical Grain Size Distribution curve from different TBM tunnels and geology (Jacques Burdin)

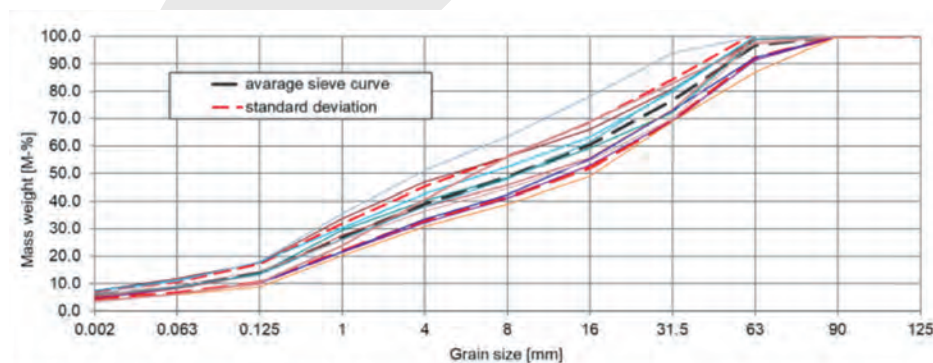


Figure 27 : Typical TBM Grain Size Distribution curve from the same project in hard gneiss with average and standard deviation (Cédric Thalmann)

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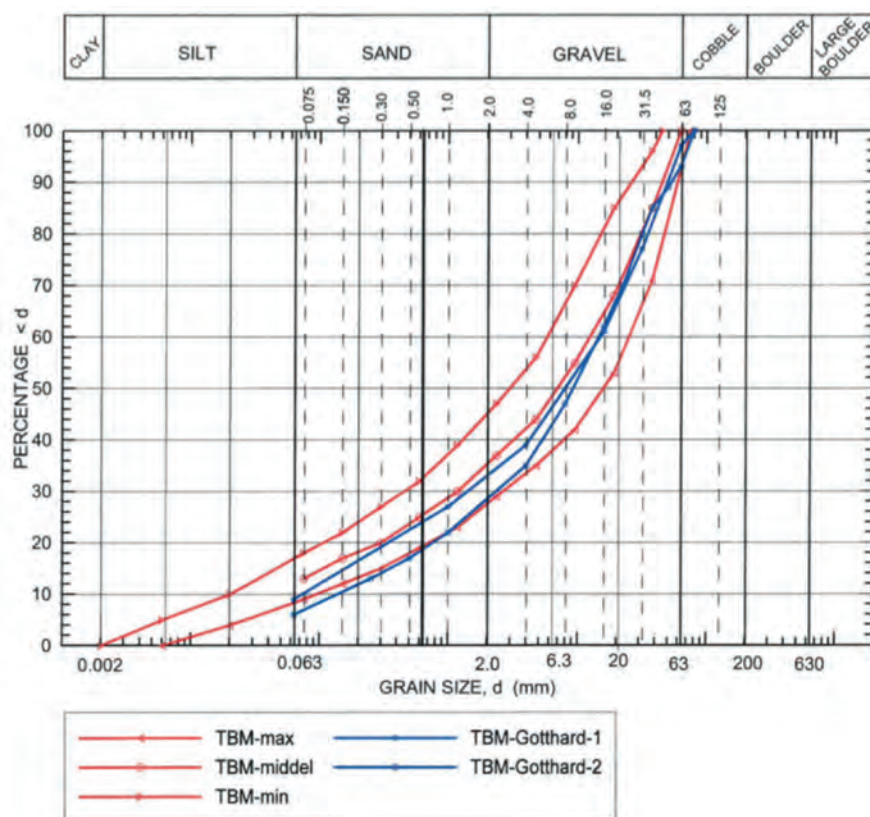


Figure 28 : Grain Size Distribution (GSD)-curves from TBM tunnels.

Furthermore, TBM tunnel muck has a generally low/reduced crushing resistance and produces more fines when compacted. The material is also water sensitive and contains a fraction of fines that will retain water. Figure 30 and 31 illustrate finely graded muck from a TBM tunnel after passing through and solids separation plant.

Surface roughness and presence of sharp edges improve the bond between aggregates and concrete but reduces workability and require greater quantity of water and cement, resulting in cost increase. Typical GSD curve from blasted rock is presented as comparison to TBM GSD envelope in Figure 32. The GSD-curves from TBM tunnels depends also on the rock type, size and distance between discs and its physical properties as well as the thrust force of the TBM machine.

Excavated materials from TBM tunnels have also been used for improvement of tracks and trails in recreational areas and parks and improvement of soil for agricultural purposes.

GSD curves from different hydropower tunnels and different geology excavated with TBM in Norway, are presented in Figure 33 (Statkraft/NGI). The results show little variation, and most of the spoil samples appear to be well graded. From these examples, it may be concluded that rock type and mineralogy, tunnel diameter and TBM manufacturer, do not play an important role regarding particle size distribution for hard rock TBM tunnels. However, as already mentioned, the drilling process (i.e. use of cutting tools, cutter load, cutter spacing etc.) is crucial for controlling the particle size distribution.

Figure 31 : Portland West Side Combined Sewer Tunnel Granular tunnel muck (slurry TBM) loaded on barge for marine site disposal. (photo from B. Fulcher).

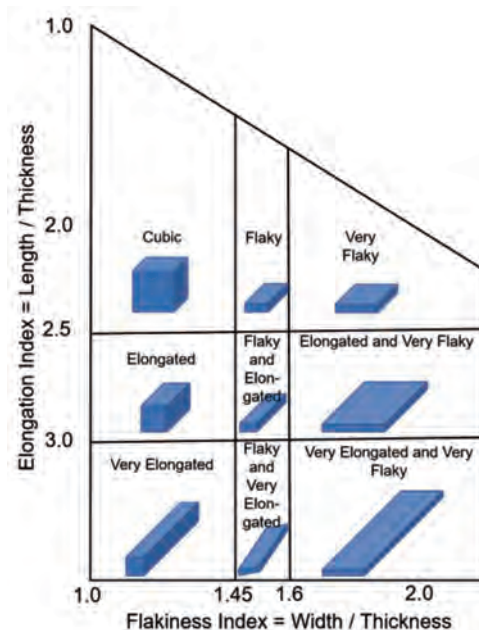


Figure 29 : Particle shape of TMB tunnel muck ("Elongation Index" is the ratio between particle length and thickness, while "flisighet" (flakiness) is the ratio between the particle width and thickness). Generally, particles from TBM tunnels are in the red area of the figure.



Figure 30 : Portland West Side Combined Sewer Tunnel muck (slurry TBM) loaded on barge for marine site disposal. (photo from B. Fulcher).



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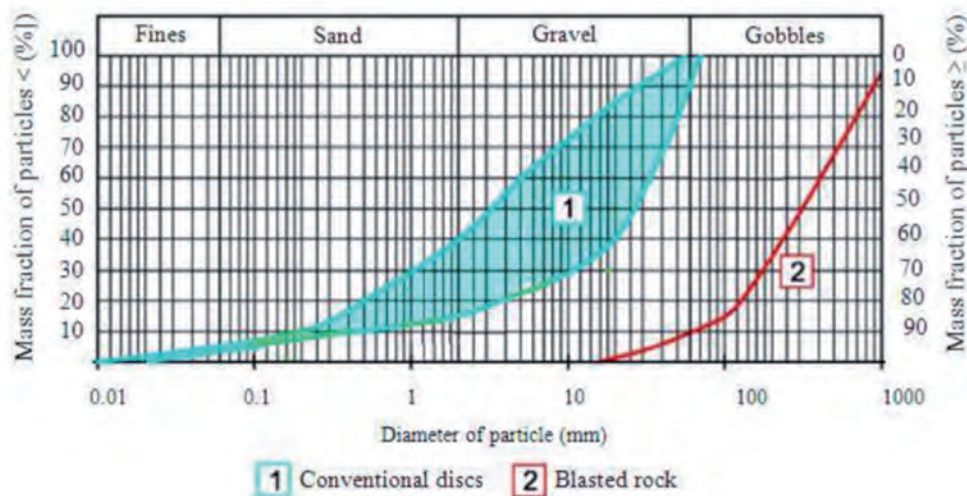


Figure 32 : Grain size distributions for different excavation techniques: TBM excavation and blasted rock.

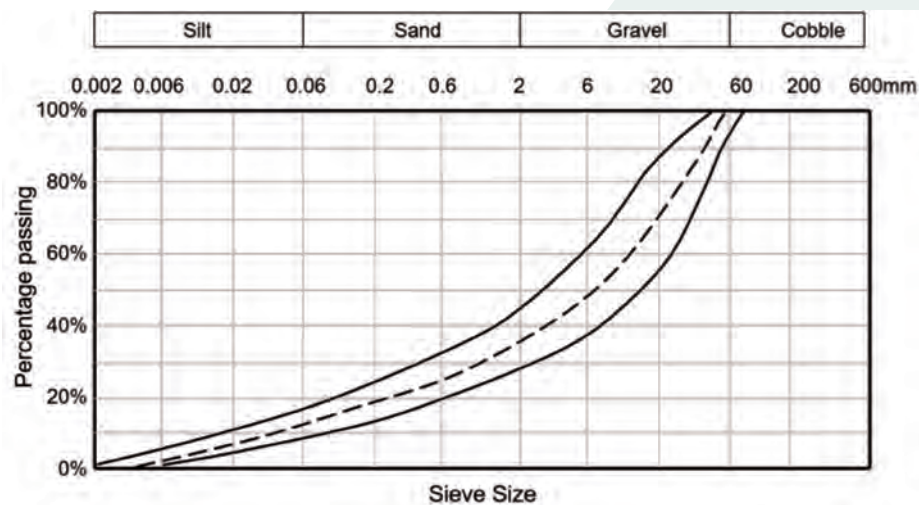


Figure 33 : Grain Size Distribution curves from various TBM tunnels in Norway (Statkraft/NGI).

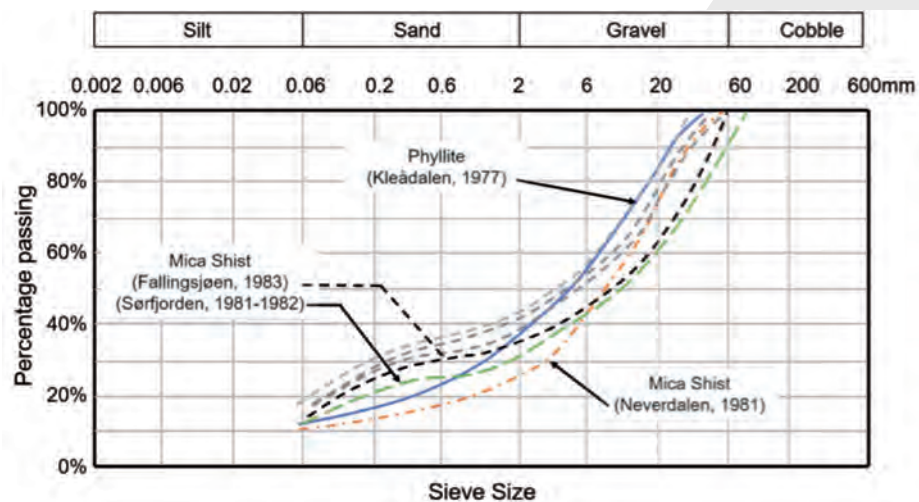


Figure 34 : Grain Size Distribution curves from various TBM tunnels in Norway (Statkraft/NGI).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

The diagram in Figure 35 compares the particle size distribution of tunnel muck from drill and blast tunnels and TBM tunnels. As the GSD curves have shown, the diagram shows more gravel and cobbles in drill and blast tunnel muck, and more sandy, silty materials from TBM tunnels.

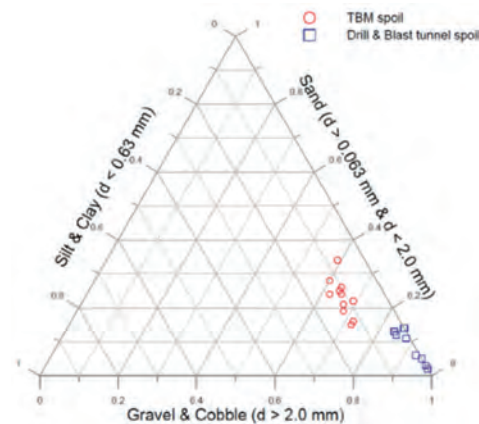
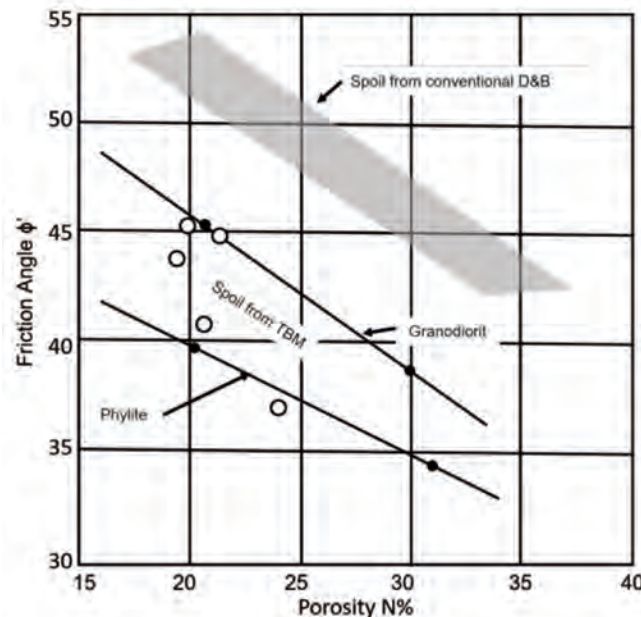


Figure 35 : Diagram with typical particle size for drill and blast TBM tunnel muck.

Figure 36 compares the friction angle of TBM and drill and blast tunnel muck tested with various porosity/density. While muck from drill and blast tunnels has friction angle from 45° to 55°, the friction angle from TBM tunnels varies between 35° to 45°. The tests are from Norwegian projects, phyllites and crystalline rock (Statkraft/NGI).

Figure 37 shows Standard Proctor test results on different samples from TBM tunnels. The Maximum Dry Density (MDD) varies between 2,180 and 2,270 kg/m³ with a water content between 6% and 8%.

Investigation results on possible revegetation use of TBM tunnel spoil performed by NVE 1985 to 1986 indicates that the spoil has favourable ability to store water in the upper unsaturated zone, has a higher cation exchange capacity and larger surface area in the fines than normal sediment particles, and has a great potential for revegetation and agricultural use. Similar tests performed in Sweden (Reference 13) give similar results, that the fines, or "rock powder" in TBM spoil may be used to improve the fertilizer for revegetation.



Friction angle, Φ , depending on porosity, n . TBM spoil gave approximately 9-10° reduction of Φ compared with rock from D&B.

○ Friction angles measured on crushed rock for impervious core in rockfill dam

TBM – spoil appears with higher cohesion values from triaxial tests (75 – 145 kN/m²)

Figure 36 : Friction angles of drill and blast tunnel muck compared with TBM tunnel muck.

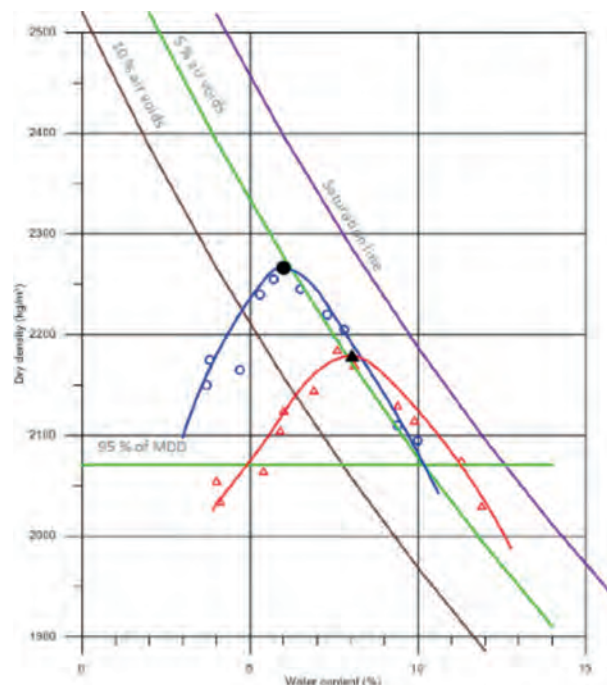


Figure 37 : Standard Proctor test results on TBM samples (Statkraft/NGI).

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4.4.1. Typical Strengths of Different Rock Types

Typical strength (Unconfined Compression Strength UCS) are presented in Table 3.

ITEM	ROCK TYPES GENERAL CLASSIFICATION	DENSITY	STRENGTH (UCS)
		g/cm³	MPA
1	Gabbro	3,15	180 to 300
2	Amphibolite	3,15	100 to 250
3	Basalt	3,10	190 to 400
4	Diabase	3,10	160 to 260
5	Greenstone	2,85	170 to 280
6	Mica Schist	2,80	20 to 80
7	Dolomite	2,80	60 to 300
8	Phyllite	2,75	20 to 80
9	Limestone and Marble	2,75	50 to 180
10	Granite and Syenite	2,75	100 to 250
11	Gneiss (dark)	2,75	80 to 200
12	Gneiss (light)	2,70	80 to 200
13	Quartzite	2,65	130 to 250
14	Sandstone	2,60	75 to 160
15	Concrete	2,40	30 to 60

Table 3 : Rock Material Properties - Typical Strength (UCS) for different Scandinavian rock types (Reference A. Palmstrøm, Norway).

As the table shows, most of the common Scandinavian bedrock types are far stronger than concrete.

4.5. CONSTRUCTION AGGREGATES AND BALLAST

Construction aggregate (or simply aggregate), is a broad category of coarse material used in construction, such as drainage applications, base material under foundations, roads, railways, concrete and asphalt production.

Excavated tunnel materials from tunnels in tough, isotropic crystalline rock, represent excellent and valuable aggregate source for different purposes. As the figures of grain size distribution curves from embankment dam show (see Section 4.3), the muck from conventional drill and blast tunnels in crystalline rock, represents well graded material.



Figure 38 : Light processing plant for concrete production. Vestfoldbanen Railway Project, Norway, Lot 12.2 (Norwegian National Railway Authorities, NNRA).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

In the following section, some basic requirements for concrete aggregates, aggregates for bituminous material, road pavement, airports and other traffic areas plus requirements for railway ballast are mentioned, referring to relevant European Standards. Please refer to Figure 38 showing a typical aggregated processing plant. Figures 39 and 40 illustrate typical end uses for processed tunnel muck; i.e. concrete and railroad ballast, provided the material properties are favourable.

4.5.1. Some Basic Requirements

Concrete Aggregates

Basic requirements for concrete aggregates are given in the European Standard EN12620:2002+A1. The requirements are related to the geometry (size, grading, shape, content of fines and the quality of the fines), physical property and strength (resistance against crushing, wearing, flakiness, density and water absorption, durability) and chemical requirements (chlorides, sulphate content, carbonate, mica content etc.).

Aggregates for Bituminous Materials and Road Pavements, Airports and Other Traffic Areas

Basic requirements for concrete aggregates are given in the European Standard EN13043. As for concrete aggregates, the requirements are related to grain size, shape and grading, content of fines, rock strength properties, flakiness, resistance against crushing (Los Angeles value), resistance against wearing etc.

Aggregates for Railway Ballast

Basic requirements for concrete aggregates are given in the European Standard EN12620:2002+A1. As for concrete aggregates, the requirements are related to grain size, shape and grading, content of fines, rock strength properties, flakiness, resistance against crushing (Los Angeles value and SZ_{PB} value), resistance against wearing (the Micro-Deval coefficient), resistance against freezing and thawing, density, water absorption, and "Sonnenbrand" (a kind of weathering related to some types of basalts).



Figure 39 : Aggregates from crystalline rock used in road pavement and fill/masonry/rip rap around portals. The Joint Venture Rail/Road Project Dovrebanen/E6 Highway along Lake Mjøsa, Norway. (photo Sjur Krogstie).



Figure 40 : Railway ballast from crushed crystalline rock. The Joint Venture Rail/Road Project Dovrebanen/E6 Highway along Lake Mjøsa, Norway (photo Sjur Krogstie).

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4.6. TUNNEL SPOIL FROM SOFT GROUND TBM TUNNELS

Considerable attention needs to be paid to the handling, treatment and disposal of tunnel spoil generated by soft ground tunnels. (Figures 41 and 42). Unlike rock spoil, soft ground tunnel spoil more frequently has few uses and is typically more difficult to dispose. Some spoil requires secondary treatment such as drying and chemical additives to make it suitable for; over-the-road haulage final disposal in a land fill. Only small quantities can be considered for engineered fills and in manufactured products. In some locations the spoils, although naturally occurring is considered contaminated or even hazardous due to some of the following conditions (Reference 3).

- Groundwater issues
- Bentonite mixing
- Chemical mixing
- Petroleum product contaminants (residuals)

Contemporary research and tests are underway at various locations and on many tunnelling projects to determine the best methods to handle treat and dispose of spoil from soft ground tunnels. Indeed, this is a significant environmental and cost consideration. It is not unusual for a tunnelling project to be impacted solely due to the spoil disposal options and costs. In the case where environmental and social control are strict, the project may face delays and redesign if only to accommodate the flow (direction) of spoil together with the proposed (and allowable) haulage and disposal options. Figures 39 and 40 below illustrate an ordinary tunnelling project that required drying of soft ground tunnel spoil, segregation into various stock piles if tested to be contaminated, followed by conveyance for marine transport and final disposal.

The ITA Working Groups are actively studying means, methods and regional preferences and restriction for handling, treatment and disposal options for soft ground tunnel spoil material.



Figure 41: Brightwater Sewer Tunnel, Seattle, USA
Tunnel muck (EPB TBM) from shaft for conveyance to marine disposal site. (photo from B. Fulcher).



Figure 42: Brightwater Sewer Tunnel, Seattle, USA
Tunnel muck (EPB TBM) on overland conveyors to marine loading and disposal site. (photo from B. Fulcher).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

4.7. SAMPLING AND TESTING

A big variety of sampling and test methods exist for using rock materials for different purposes, physical and chemical tests, depending on the potential use of the rock material, or if there might be any risk of asbestos, radioactive, or other potential noxious materials in the rock. Requirements for sampling and testing varies from country to country, and project to project.

During the planning stage, it is necessary to carry out geological mapping, investigations, sampling and testing to classify and evaluate the potential use and suitability of the excavated rock material.

In Italy, the research program “ReMuck”, whose subject is “Innovative methods for the eco-compatible and sustainable recycling of muck from tunnels, is developed (Reference 2).

In Europe, the DRAGON Project (Development of Resource-efficient and Advanced Underground Technologies) has started as joint cooperation between Austria, Germany, Switzerland, France and UK (Reference 1). The project focuses on efficient use and recycling of excavated materials from TBM driven tunnels to obtain a substantial reduction of the demand for primary mineral resources and the amount of CO₂ emissions involved in landfilling and transport. The project sets out to solve this challenge by developing a system for an automated online sampling and characterization of physical, chemical and mineralogical properties provides the basis for assessing the suitability of the excavated material for different recycling options (Figure 43 and 44). Finding a solution to this challenge is of great economic and environmental interest. The sorted material can be used as aggregates on site or in other industrial sectors such as the cement, ceramic or glass industries, thus significantly increasing resource efficiency in tunnelling. Life Cycle Assessment (LCA) and mass flow analysis will be carried out to quantify and compare different scenarios of use and disposal.

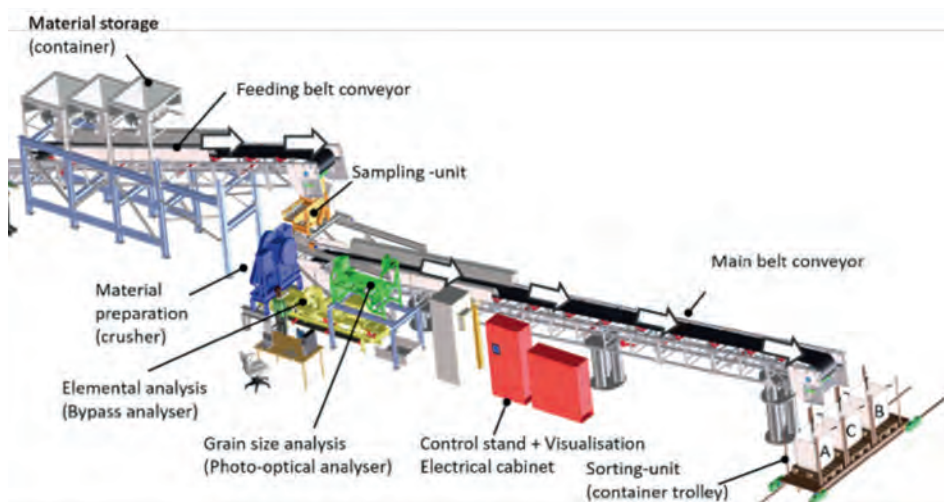


Figure 43 : Automated on-line device installed on the TBM for sampling and characterization of physical, chemical and mineralogical properties of the muck (DRAGON prototype)



Figure 44 : Automated on-line grain size analysis (Reference 1).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

4.7.1. Some Relevant Tests

As mentioned, the potential use of tunnel muck depends on several factors, such as geology and mineral composition, texture and alteration, physical parameters, hardness and strength, excavation method, handling and transport and also chemical composition. It must be pointed-out that “on-line” chemical analysis will be absolutely essential to detect the presence of dangerous components such as SO₃. In France, TELT will check the SO₃ content of excavated material (EXMAT) by using PGNA “on-line” analyzer on the Modane job site of the Mont Cenis Base Tunnel.

For construction purposes, a great attention must be given to the soft, soluble, lamellar or fibrous materials, as well as altered rock. Alkali reactive minerals must be

also checked in order to implement the use of convenient cement or binder for the concrete production. Among testing of aggregates for different purposes, the following tests are most common :

- Ductility and strength/Unconfined Compression Strength Test (UCS)
- Elastic modulus
- The Point Load Test or “Brazilian Test”
- Poisson Ratio
- Hardness
- Grain Size Distribution Test (GSD)
- The content of fines
- Compaction/density tests (Standard Proctor)
- Flakiness Test
- Geometric characteristics, Shape Index/ anisotropy
- Los Angeles Test and durability tests
- Resistance and Polishing Tests

- Abrasion Resistance Tests and Wearing Index
- Drilling Rate Index
- Density Tests
- Water Absorption Tests
- Freezing and Thawing Tests
- Alkali-Silica Reaction Tests
- Chemical tests (chlorides, sulfates)
- Petrographic analysis/mineral content
- Surface Roughness Tests
- Porosity and permeability

Requirements for testing varies from project to project, and from country to country while the test routines are more or less standardized over the world. In Table 4, some standard tests with reference to international standards are mentioned.

ITEM	DESCRIPTION OF TEST SYSTEM	REFERENCE STANDARD	
		Source	Code
1	Fragmentation Index	Modified AFNOR	p 18 to 579
2	Point Load Index	ISRM	
3	Los Angeles Test	EN	1079-2
4	Petrographic analysis	SIA	
5	Granulometric Analysis sand	SIA 162.311	162.311
6	Granulometric Analysis gravel	SIA 162.311	162.311
7	Shape of elements	EN 933-6	933-6
8	Alkali Aggregate Reaction	AFNOR	p18 to 588
9	Unit weight	EN 1097-6	1097-6
10	Water content	EN 1097-6	1097-6

Table 4 : Material Tests – Tunnel Spoil - Summary of applicable material tests and referenced codes and standards.

4.7.2. Procedures for On-Site Testing

Swiss concrete standards are based on rounded aggregates and cannot be applied one to one to crushed aggregates. a profound study (PhD-work) in collaboration with the AlpTransit Lötschberg, Gotthard and Ceneri projects has been carried out in the Swiss Federal Institute of Technology Zurich (ETHZ, Reference 14). This study defines different criteria and test methods

to be used for evaluating and controlling the quality of excavated raw material. These methods have been used and refined successfully throughout the last 20 years. This ‘on-site’ method can be applied on any type of materials (TBM, drill and blast, drill cores, quarries, etc.), is fast (less than 2.5 hours), and results are highly reproducible. The developed procedure is modularly and comprises a number of tests with different statements relating to rock

parameters. Depending on requirement or visual change of the rock quality, individual or several examinations can be carried out. This method of quality assessment and triage between suitable and not-suitable excavation material is a continuous process that takes place in an on-site laboratory, where muck quality is determined according to its rock hardness and petrography (inappropriate components).

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

Fresh TBM muck has never undergone natural selection process (e.g., water erosion). Thus, it has to show sufficient rock strength before being processed into aggregates. The minimal compressive strength requirements are not defined by European standards. Aggregate rock

strength should be at least two times harder than the concrete hardness class. According to European standards, aggregate hardness is determined by the Los Angeles test. Because the latter is time consuming and can only be applied onto aggregates, the excavated raw material hardness is

evaluated using the point load index and the LCPC Breakability Index (French norm AFNOR P18-579). The results of the LCPC method linearly correlate with those of the Los Angeles test. Moreover, during this test, the Abrasivity Index ABR of the rock can also be calculated (Table 5).

TEST METHOD	REFERENCE STANDARDS	GUIDELINE VALUES*	FREQUENCY OF TESTS
Breakability Index	AFNOR P 18-579 Procedure modified for TBM muck	$\leq 60 - 70 [-]$	15 TM (Tunnelling Meter)
Point Load Index I_{SSO}	ISRM 1985 Procedure modified for TBM muck	IS50 parallel: $\geq 2.0 - 2.5 [N/mm^2]$ IS50 isotropic: $\geq 3.0 - 3.5 [N/mm^2]$	75 TM (Tunnelling Meter)

* These requirements are modularly depending on the geology and concrete requirements.

Table 5: Rock Hardness Requirements - Abrasivity Index ABR tests and frequencies on rock use the standards listed in this table.

Besides having adequate rock hardness, the muck also must fulfil petrographic requirements. An initial appraisal of the muck is given by a macroscopic description and classification of the rock material (EN 932-3). If the sand fraction is also recovered (e.g., to produce concrete), then, the content of unsuitable components in the crushed sand must be determined and monitored. Unsuitable minerals are described in the Swiss standard SN 670 115 :

«*phyllosilicate-rich grains (consisting of more than 50% of phyllosilicates on the surface or in the material), argillaceous rock grains, hydrothermally converted rocks (e.g., mica and chlorit-rich schist and gneiss, etc...).*

Coarse grain crystalline rocks (e.g., granite, gneiss, marble) create often very brittle chippings that can be easily broken with a fingernail in the fractions below 11mm. Chloride containing rocks (halite, etc.), sulfides (pyrite weathered some, marcasite, pyrrhotite, etc.) and sulfates (gypsum, anhydrite) as well as organic materials such as coal, lignite, peat, slag, wood and partially petrified wood are also unsuitable.»

Mica (phyllosilicates) is a group of unsuitable components, which form platelets during raw material crushing. These accumulate in the sand fraction and change the properties of fresh and hardened concrete. Laboratory mortar tests have shown that not only the

quantity but also the grain size and type of free mica influence the properties of fresh and hardened concrete (Reference 14). They have also shown that mainly mica greater than 0.125 mm exercises a negative influence. Fine mica (< 0.125 mm) did not influence the mortar properties negatively; on the contrary, the slump and the tensile strength had even increased.

Layer silicates in crystalline or metamorphic rocks are problematic when their concentration > 20% by volume in the raw sand. Mica content (reference group 0.25/0.5 mm) should be held under 35% particles in the crushed sand as noted below in (Table 6).

TEST METHOD	REFERENCE STANDARDS	GUIDELINE VALUES*	FREQUENCY OF TESTS
Macroscopic petrographic of the tunnel face	SN 670 115	Mica content : • \leq approx. 20 particle - % Petrographic unsuitable layers : • \leq approx. 20 particle - %	\pm Daily (during geological mapping)
Petrographically Inappropriate Components (excluding. phyllosilicates) in the excavated material: fractions 1/4mm (microscopic); 4/22, 22/128mm (macroscopic)	Based on SN 670115 und SIA 162 /1	≤ 10 [weight-%]	150 TM (Tunnelling Meter)
Free Phyllosilicates: in the crushed sand (fraction 0.25/0.50 mm)	SN 670 115	≤ 35 [particle-%]	150 TM (Tunnelling Meter)

* These requirements are modularly depending on the geology and concrete requirements.

Table 6 : Petrographic Requirements
Summary of standard petrographic analysis tests and suggested frequencies on rock material.

4 >> OPPORTUNITIES FOR TUNNEL SPOIL

4.8. ALTERNATIVE EXCAVATION METHODS

Besides conventional drill and blast plus TBM tunnelling, use of EPB (Earth Pressure Balanced Shield) (Figures 45 and 46) for soil and mixed face conditions, roadheader for soft rock, and common excavation for soft rock and cut and cover tunnels are used. While tunnelling in hard rock may produce good quality muck, tunnelling in soft rock and soil produces tunnel muck of poorer quality in most cases. Exception may be cut and cover tunnel excavation in good quality gravel and sand. See Figure 47.



Figure 45 : EPB machine under mobilization at the C1 Andora – San Lorenzo Railway Link, Italy (Martelli Francesca, Italy).



Figure 46 : One of the world's largest EPB machine (12.9m diameter) ready for the very challenging Port Miami Tunnel, in Miami, FL (photo from Herrenknecht).



Figure 47: Roadheader used in soft rock (site unknown).

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At the Taiwan High Speed Rail project (Figure 48), excavated soil, stabilised with cement, was to some extent used to fill-up small valleys crossing the tunnel alignments and then tunnelling thorough, to avoid more expensive and complicated intermediate sections between mined tunnels and cut and cover sections.

Further handling and treatment of EPB tunnel muck are discussed in Chapter 5, Challenges.



Figure 48 : Soft rock tunneling, the Taiwan High Speed Rail, excavated by backhoe excavators and no explosives used (Rohde 2002).



Figure 49 : Tunnel muck from EPB TBM machine, probably not useable for construction purposes, and must be considered as waste material

5 >> CHALLENGES

Besides opportunities, there are also challenges and potential conflicts related to excavated material from tunnels and underground caverns. Potential environmental challenges with excavated rock from tunnels and caverns might be related to the rock/soil itself, excavation methods, logistics, handling and transport as well as temporary storing and permanent depositing.

In many countries, the tunnel spoil is defined as waste material, if no applications are possible or no solutions can be provided. National regulations should provide a clear distinction between “waste” materials and products for use from tunnel spoil like in France and Austria (References 15 and 16).

As seen from different examples in Chapter 2, large tunneling projects require large space for the logistics, handling, processing and transport of tunnel muck. However, for urban tunneling and tunnels in cities, large space is a great challenge.

5.1. GEOLOGY AND GROUND CONDITIONS

Some of the challenges might be related to geology and rock type. For some rock formations, the minerals and chemical composition of the bedrock might be even harmful to the environment and classified as contaminated waste in concentrated form so the excavated material must be treated as such. Some rock types, like alum shale, has a very high content of radon and high risk of radiation when exposed to air. Another example is the Potential Acid Sulfate Soil (PASS) at the EPB/TBM driven twin tunnels at the Perth New MetroRail City Project in Australia. At the Northeast Interceptor Sewer Tunnel in USA the sedimentary rock (sandstone, siltstone and old alluvium) was naturally contaminated by hydrocarbons and man contaminated sedimentary material from Los Angeles Basin, potentially gassy with special conditions. Also, the drain water from such soil and rock types will be contaminated, so the rock spoil must be sealed and drain water controlled, to

avoid spreading the contamination.

Rock types containing asbestos minerals might also create problems during construction and after storage. Primarily, the problems are related to Health and Safety aspects and dust during construction, but also the storage of asbestos minerals has to be treated carefully to prevent problems to the environment.

As an example, on Health and Safety related issue, at the Lot 12.2, Contract E07, the Vestfold Railway line between Larvik and Porsgrunn, Norway, hornblende was discovered during drilling and excavation of the portal/cut and cover entrance to Storberget tunnel, creating asbestos and harmful dust.

To identify any potential problems related to the rock, geological mapping,

sampling, analysis and testing of minerals and chemical composition is necessary. In some cases, cut and cover tunnels are crossing areas with contaminated soil. The soil must be handled, treated and stored in a safe way, to avoid negative impact on the environment.

In the mining industry, the waste from processing (flotation and chemical treatment) is contaminated and must be stored in a controlled way or sealed if necessary, to avoid negative impact on the environment. Control and monitoring of drain water from waste deposits are required.

5.2. EXCAVATION

Even the excavation method might create negative impact on the environment. See Figures 50 and 51.



Figure 50 : Charging at the OREA Sewer Plant Extension, Norway. (Photo E. Hannestad, Sweco Norge AS).

5 >> CHALLENGES

In conventional drill and blast tunnels and caverns, chemical remains from explosives, such as ammonium and nitrates, might occur, and the chemical remains in process water from tunnels and caverns may create negative impact in recipients if it goes direct to the recipients (streams and rivers) without control and treatment.

In mechanized tunneling (TBM, EPB), use of different chemicals, foams and slurries are often required for soil conditioning during excavation. See Figures 52 and 58. Various soil conditioners (foaming additives, polymers, etc.) have different properties and chemical composition, and the potential risk for environmental damage varies from none high. Since the soil conditioner is injected ahead of the cutter, the working chamber and/or screw conveyor, the excavated soil might be contaminated from the conditioning product. Depending on the environmental risk related to the soil conditioning product, the excavated soil might be used directly, after treatment or treated as waste and handled as such. Relevant treatment of EPB-TBM excavated soil is drying/stockpiling, washing and grain size separation before use. These aspects are important issues for the management of soil excavated by TBM with EPB technology (Reference 17). See Figures 53 to 57 for illustrations of a very large diameter EPB TBM used in Seattle, Washington, USA for the SR 99 highway tunnel.

Use of cement in grout and concrete structures (sprayed or in situ cast) result in high pH values in drain and process water in tunnels and underground caverns. Water control is necessary, and adjustment of the pH value might be needed before leading the tunnel water to recipients.



Figure 51 : Drill and blast muck pile from the Rosten HEPP (Photo Ø. Fæhn, Skanska).



Figure 52 : Break-through of two EPB machines at the Bologna railway junction, Italy.

5 >> CHALLENGES

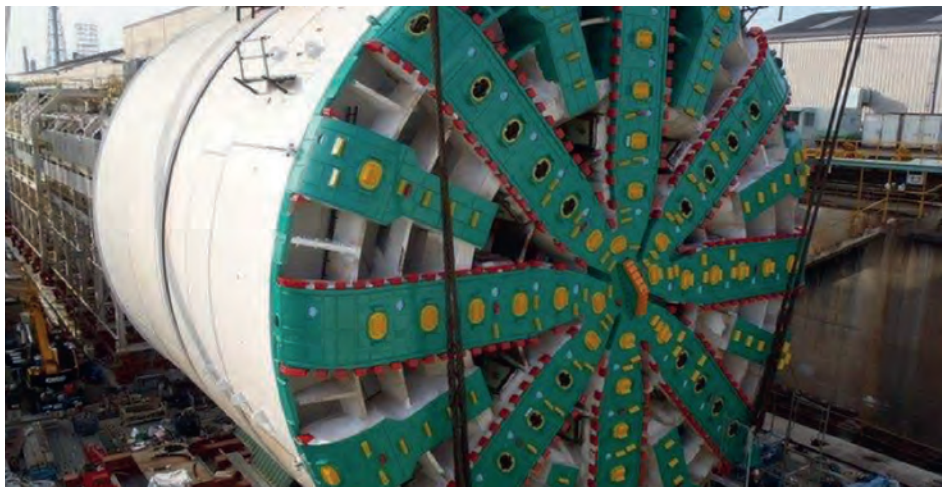


Figure 53 : "Bertha", 17.4m diameter EPB shield machine, for the SR 99 tunnel in Seattle, Washington USA, fully-assembled for shop testing.



Figure 54 : "Bertha" in action in recovery shaft at the SR 99 tunnel in Seattle, Washington USA.



Figure 55 : Screw conveyor of "Bertha" at the SR 99 tunnel in Seattle, Washington USA.

5 >> CHALLENGES

5.3. LOGISTICS, MANAGEMENT, HANDLING AND TRANSPORT OF TUNNEL MUCK

The possibility of using the tunnel spoil coming both from conventional and mechanical tunneling, have a great influence on the logistics, environmental and economic aspects of a tunnel project.

For optimizing the logistics, handling and management of the tunnel muck, preparation of a tunnel muck management plan is essential. As part of a tunnel muck management plan, the following issues are of utmost importance :

- Potential use of the tunnel muck
- Transport methods, transport routes and logistics
- Intermediate storage and permanent deposit areas
- Tunnel muck processing plant (sorting, crushing, concrete and asphalt production)
- Environmental issues like noise and dust emissions, traffic safety, contaminated drain water

Transport of tunnel muck represents a problem in populated areas especially in urban and recreational areas. Heavy transport creates noise, dust and pollution and represents an extra risk for traffic accidents on public roads. Therefore, careful planning of logistics and transport routes, mapping of potential conflicts and negative impacts and risks, as well as preparation and implementation of mitigation measures are very important to decrease the potential problems and risks related to transport of tunnel muck. In any case, use of excavated rock in the project itself or projects in close vicinity will be of great benefit to the environment, and will also reduce the CO₂ footprint related to transport of tunnel muck.



Figure 56 : Conveyor belt transport system at the SR 99 Tunnel in Seattle, Washington, USA.



Figure 57: Muck handling and barge loading for the SR 99 project in the harbor of Seattle, Washington, USA.

5 >> CHALLENGES

Another example of tunnel muck handling in urban areas is construction of the 72nd Street Station large and shallow rock caverns in New York City (Reference 7). The project included 13.7 km tunnel, 16 stations whereof 10 cut and cover, and 6 mined underground caverns.

At the 72nd Street Station, a volume of 150,000 m³ of tunnel muck was handled and transported in the very urban environment of Manhattan. The technical considerations were critical, including important supporting concerns including electric power, surface equipment, and managing the relationship with the

residential community. The major rock excavation and concrete construction underground necessitates development of a large array of logistics support within the minimal space at the site surface. Please see Figures 60 and 61 that clearly illustrate the scale of the work and the street-level congestion at the work site.

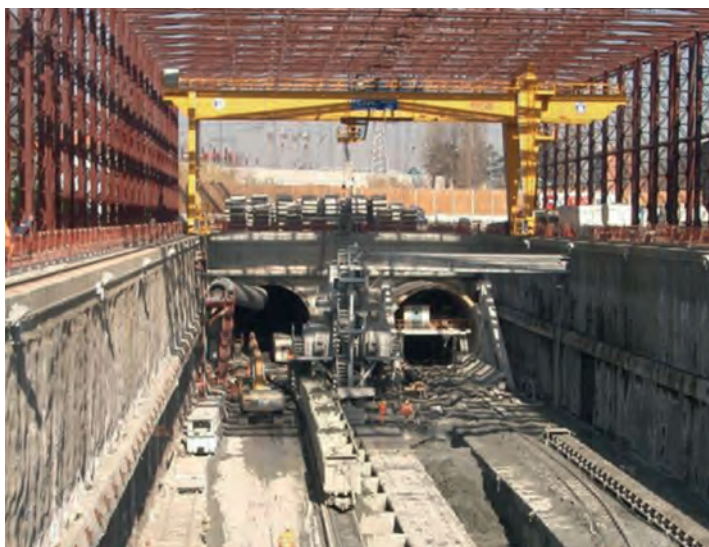


Figure 58 : Logistics at the A6 Bologna Railway Junction, Italy.



Figure 59 : Hauling of tunnel muck via vertical shaft by crane. (site unknown).



Figure 60 : 72nd Street Station Cavern during drill and blast excavation and initial support phase, Second Avenue Subway, New York City. (Photo Brian Fulcher).



Figure 61 : 72nd Street Station Cavern spoil handling facility at street level during drill and blast excavation and initial support phase, Second Avenue Subway, New York City. (Photo Brian Fulcher).

5 >> CHALLENGES

For transport of tunnel muck in tunnels, and over short distances outside the tunnels, use of conveyor belt might be a benefit for the environment, at least for the internal work environment plus health and safety for the workers. Conveyor belts are commonly used for muck transport in TBM and EPB tunnels. Tunnel rail systems remain the most popular as shown in Figure 62.

In particular, noise and dust from dumping of tunnel spoil, dozing and compaction of embankment and fill as well as from crushing plants (Figures 63 and 64) represent a problem to the environment. To reduce the negative impact from these activities, dust prevention with water, noise damping and restrictions on time and duration of these activities in urban and populated areas are normally practiced. Cleaning of transport vehicles is required in urban areas to reduce mud and dirt on public roads.

5.4. TEMPORARY STORAGE AND PERMANENT DEPOSITS

On large tunnelling contracts, the production of excavated material might be far beyond the local need and consumption, and distance to the market might be far. To avoid transport over long distances, there is need for temporary or permanent storage of the tunnel muck within as short distance as possible to the project. If the rock quality is good, free space might be offered from land owners. In many contracts, the Contractor is offered to take responsibility for the excavated material as part of the contract, since the Contractors often have better contact with the market and of the potential use of excavated material in other ongoing projects.

If well suited localities for depositing excavated rock is found, site preparation, instructions for filling (compaction requirements), landscaping etc. should be prepared. Water control, landscaping and replanting of the final deposit are recommended. Stability of the foundations as well as the fill material



Figure 62 : Rail transport in tunnel.



Picture 63 : Crushing and sieving plant for preparation of aggregates for different purposes. Follo Line Railway Tunnel Project, Norway.

5 >> CHALLENGES



Figure 64 : Mobile crushing plant used for minor temporary works. Follo Line Railway Tunnel Project, Norway Bjørnar Gammelsæter 2015.

itself should be evaluated, in particular for soft and weak rock types.

The risk of polluted drain water from the stored tunnel spoil has to be assessed. Besides clean hard rock of good quality, many geological formations contain soft and weak rock types, rock soluble in water or rock with soluble minerals representing risk of pollution to the wetlands and streams in the vicinity. Some rock types represent a risk of radiation, like pr. example alum shale. Tunnel muck from such geological formations must be handled, treated and deposited as contaminated soils to protect the environment. Some of these rock types require to be wrapped and sealed in membranes and/or packed in impervious clay.

Careful attention should be paid if chemical grout, foam or slurries for EPB and TBM tunnels have been used. Also, cement grout as well as spoil from

sprayed concrete, in situ cast concrete and additives may represent a potential problem, creating high pH values in drain water from the tunnel spoil deposits. Sediment basins, water control and monitoring might be required to avoid negative impacts to the environment and pollution of wetlands, small streams and rivers.

6 >> CONTRACTUAL ISSUES

During preparation of the contract documents, special attention should be paid to give instructions to the bidders on environmental issues. Furthermore, remedial measures should be specified and included as cost bearing elements in the Bill-of-Quantities.

As important environmental issues in the contracts, the following can be mentioned:

- Essentials from Environmental Impact, Risk and Opportunity Assessments to be addressed
- Environmental Plan and Monitoring Program to be implemented in the contract
- Tunnel Muck Management Plan to be implemented in the contract and specifications
- If the excavated material shall be used in the project, testing program, specifications and requirements should be prepared and implemented in the contract
- Instructions and restrictions for handling and transport to be implemented
- Instructions and restrictions for depositing of tunnel spoil (compaction, landscaping, control and monitoring of drain water etc.) to be implemented
- Contractors and owner responsibilities and risks related to the environment to be addressed in the contract
- Environmental measures to be specified and implemented in the Bill-of-Quantities (BOQ)
- Contractors to be requested/encouraged/awarded for environmentally favorable solutions

7 >> RECOMMENDATIONS AND CHECK LIST

7.1. RECOMMENDATIONS

For preparation and good handling of excavated material from tunnels, the following recommendations are given:

7.1.1. Planning Stage

- Geological mapping, sampling and testing to assess potential use as well as potential problems or hazards related to the excavated rock
- Environmental Risk and Opportunity Assessment (EROA) to identify potential problems as well as potential opportunities related to handling and use of the excavated material
- Establish an Environmental Plan and Monitoring Program related to handling and use of excavated material
- Prepare tunnel Muck Management Plan
- Planning of landfill areas with stability assessments, landscaping, replanting if necessary, drain system with settlement basins, control and monitoring of drain water
- Transport and logistics by finding safe transport routes from the tunnel to the muck deposits with minimum of negative environmental impacts and a minimum risk of accidents, preparation and implementation of mitigation measures.
- Filter curtain to avoid spreading of fines in lakes, rivers and sea
- Prepare for crushing plant, concrete and asphalt production plant
- Traffic safety measures
- Prepare for long time storage of tunnel muck

7.1.2. Preparation of Contract Documents

- Instructions to the Contractor, environmental plan and monitoring program to be implemented in the contract documents
- Mitigation measures to be specified and implemented in the Contract documents and Bill of Quantity
- Implementation of Tunnel Muck Management Plan

7.1.3. Construction

- Environmental and monitoring program to be followed-up by Client and Contractor

7.1.4. Operation and Post Operational Stage

- Environmental and monitoring program to be followed-up by Owner

7.2. CHECK LISTS

7.2.1. Planning Stage

- Geologic survey, data collection, sampling, testing and classification
- Evaluation of potential use
- Environmental Impact Assessment related to excavated materials from the tunnels
- Identify risk elements, opportunities and challenges related to tunnel muck
- Transport and logistics
- Need of processing
- Temporary and permanent disposal

- Prepare Environmental Monitoring Program
- Prepare specifications for excavation, handling, transport and depositing of excavated material from the tunnels

7.2.2. Contract

- Instructions to Contractor on environmental issues, risks and remedial measures
- Environmental Monitoring Program (EMP) to be implemented in the contract
- Mitigation measures to be specified

7.2.3. Construction Stage

- Environmental Monitoring Program (EMP) to be followed-up

7.2.4. Post Construction Stage

- Environmental monitoring program to be followed up as required
- Monitoring of deposits or fills, seepage and drain water

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

8.1. QUESTIONNAIRES

In order to collect information from different projects around the world, a questionnaire was distributed to the Member Nations of ITA. The questionnaire distributed is presented in Enclosure 1. All together 59 cases were received from different nations. These included the following ;

- Australia 2 cases
- Czech Republic 18 cases
- Denmark 1 case
- France various
- Iceland 3 cases
- Italy 8 cases
- New Zealand 1 case
- Norway 4 cases
- Switzerland various
- Taiwan 2 cases
- Turkey 9 cases
- United Kingdom 1 case
- United States 10 cases

France and Switzerland completed the questionnaires with information fed directly to this report through their participation in the Working Groups. In addition, information from the DRAGON program (joint cooperation between Austria, Germany, Switzerland, France and UK) and a report on environmental issues prepared by students from the Warsaw University of Technology, Poland. The questionnaire covered the following :

- 25 road tunnels
- 13 railway tunnels
- 3 metro tunnels
- 3 hydropower tunnels
- 6 subway tunnels
- 3 water supply tunnels
- 3 sewer and waste water tunnels
- 1 linear accelerator tunnel

A total of 36 of these tunnels were excavated by conventional drill and blast, 13 with TBM or EPB, 3 with roadheader and one cut and cover tunnel. Use of tunnel muck for the reported projects from different ITA Member Nations is shown below in Table 7.

COUNTRY	PROJECTS AND APPROXIMATE USE OF TUNNEL MUCK						TOTAL PROJECTS
	100%	100-75%	75-50%	50-25%	25-0%	0%	
Australia	1	-	-	-	-	1	2
Czech Republic	7	-	2	2	4	3	18
Denmark	1	-	-	-	-	-	1
Iceland	-	2	-	-	1	-	3
Italy	7	-	-	-	-	1	8
New Zealand	-	-	1	-	-	-	1
Norway	1	-	1	1	1	-	4
Taiwan	2	-	-	-	-	-	2
Turkey	3	1	-	2	2	1	9
United Kingdom	-	-	-	-	1	-	1
United States	10	-	-	-	-	-	10
Total	32	3	4	5	9	6	59

Table 7: Handling, Treatment and Disposal of Tunnel Muck (* not specified)
Summary of projects reporting on the percentage handling, treatment and disposal of tunnel spoil material.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

As the table shows, in more than 50% of the reported projects, 100% of the tunnel spoil was used. In many of these projects, the bedrock was of very good quality (granites, gneiss, basalt, rhyolite) which were used as aggregates, subbase or upper base in road and railway construction. At the Eidanger Tunnel, Norway, the limestone was sold for cement production to Norcem with location within the project area. Bedrock of poorer quality, gravel and glacial deposits, were used as embankment fill and land reclamation, as the tunnel muck from the City Ring, Denmark and several of the Italian projects.

Environmental issues, challenges and conflicts mentioned were geologic formations with Potential Acid Sulfate Soil (PASS) and other contaminants (Perth New MetroRail City Project, Australia, conflicts in residential areas, parkland, national parks and recreational areas (noise, vibration, dust and traffic problems), contaminated soils (cut and cover tunnels), runoff water from deposits of tunnel muck, foam from EPB machines as some examples. In the UK some of the excavated material will be

used to raise the ground level to form bird sanctuary in Thames estuary.

8.2. SELECTED CASES STUDIES

For illustration, two projects in Taiwan, one from Australia, one from the United Kingdom as well as two projects from Switzerland have been selected as examples. A longer description is given for the Gotthard Base Tunnel.

8.2.1. Suhua Highway Improvement Project, Taiwan

The Suhua trail was first built in 1870s for the military and was improved to accommodate passenger cars and trucks in the 1930s. The existing Suhua Highway zigzags and has large grade differences. However, this highway is the only route connecting eastern and northeastern Taiwan. The Suhua Highway is frequently blocked due to the instability of adjacent slopes caused by massive precipitations and large earthquakes; these events occur frequently. This instability can also result in human fatalities. For example, 26 passengers died on the highway during

Typhoon Megi in October 2010. The Suhua Highway Improvement Project (hereafter referred to as the Suhua Project), which began in 2011, focused on improving the safety of dangerous mountainous sections.

The Suhua Project tackles three major sections, with a total length of 38.8km: the Suao-Dongau section (Section A; approximately 9.7 km long), the Nanau-Heping section (Section B; approximately 20.0km long) and the Hezhong-Qingshui Section (Section C; approximately 9.1km long) (Figure 65). These three sections have eight tunnels with a total length of 24.5km, accounting for about 63% of the length of the sections. Table 8 below summaries tunnel information. In total, 6,585,500 m³ rock are expected to be excavated.

LOT	TUNNEL NAME	MAJOR ROCK TYPES	LENGTH (m ³)	VOLUME (m ³)	REMARKS
A1	Suao	Slate	240	58,000	Twin-bore
A2	Dongao	Slate, schist, gneiss amphibolite, marble	3,320	899,000	Twin-bore
A3	Dongyue	Schist	220	55,000	Twin-bore
B1	Wuta	Schist	458	107,500	Twin-bore
B2	Guanyin	Schist, marble, chart	5,700	1,689,700	Twin-bore
B3	Guanyin Gufeng	Quartzite, marble, schist	2,260 4,589	1,979,600	Twin-bore
C1	Zhongren	Gneiss, marble	4,700	1,163,000	Twin-bore
C2	Renshui	Marble, schist	2,885	633,700	Single bore with emergency tunnel

Table 8 : Characteristics of Tunnels in the Suhua Highway Improvement Project, Taiwan
Summary of tunnel excavated quantities. In total, 17,052 m³ rock are expected to be excavated.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

The excavated rocks are mainly marble, amphibolite, gneiss, schist, and slate, all of which, except for rocks from faulty zones, have good engineering properties. Therefore, each of the three construction bids plans to use as much excavated rocks as possible at the beginning of the project. Minimizing the distance excavated rocks must be transported and minimizing environmental impact are key goals in the design stage.

In Figure 66, Section A, excavated rocks are mostly from the Dongao Tunnel (Construction Lot A2). The surplus amounts of excavated rocks from the southern portal and northern portal sites after use in adjacent construction bids, are approximately 601,000 and 454,000 m³, respectively. The locality north of Section A lacks sufficient amounts of aggregate and earth for civil work and applies for the excavated rocks from the Suhua Projects. As such, surplus excavated rocks are given to the local government, and then given to quarries and construction companies. Both highways and railways are utilized to transport these surplus rocks. A truck is used to carry rocks from a tunnel portal to the closest railway station (the Dongao Station for the southern portal, and the Yongle Station for the northern portal) (Figure 67). A platform wagon with containers transport excavated rocks to a government temporary transfer post (Figure 68) at Xinma Station. The haul distances for trucks and wagons from the southern portal are 2km and 11.9 km, respectively, and those from the northern portal are 0.8km and 6.5 km, respectively. The expected reduction in equivalent carbon dioxide achieved by using the railway to transport excavated rocks from the Section A exceeds 1,000 tons.



Figure 65: Location and route of the Suhua Improvement Project.



Figure 66: Location and route of the Suhua Improvement Project.



Figure 67: Planning for transportation of excavated rocks for Lot A2 in the Suhua Improvement Project.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

In Section B, excavated rocks are mostly from the Guanyin Tunnel (Construction Lot B2 and Lot B3) and the Gufeng Tunnel (Lot B3). The surplus volumes of excavated rocks are 26,200,000 m³ and 12,600,000 m³, respectively. Some of excavated rocks from the Gufeng Tunnel are marble, which have a volume of about 520,000 m³ and are then transformed into appropriate raw materials for cement production. Therefore, two embankments are designed for the adjacent lots: the northern Nanao embankment (Lot B1), which can accept 25,500,000 m³ of rock; and the southern Hanben embankment (Lot B4), which can accommodate 14,500,000 m³. The Section C will also provide excavated rocks for the Lot B4. A truck is utilized to carry rocks between adjacent lots in the section using an abandoned railway tunnel and a temporary road. A platform wagon with containers is used to transport rock between sections for Lot B4; it also transports the graded marble. Figure 69 shows the landscape of the Lot B1 Nanao embankment lot that is adjacent to the highland beach of Nanao South Creek, which provides a pond to enhance landscaping and for ecological protection.

In Section C, marble volumes of 6,000,000 m³ and 6,300,000 m³ that were excavated from the Zhongren Tunnel (Lot C1) and the Renshui Tunnel (Lot C2), respectively, are graded into appropriate raw materials for cement production. The volume of surplus excavated rock from the Zhongren Tunnel (Lot C1) and the Renshui Tunnel (Lot C2) is 6,400,000 and 700,000 m³, respectively. This surplus excavated rock is transported to Lot B4 on a railway, and the valuable marble is sold to cement plants, quarries, and construction companies.

Utilization of excavated materials from tunnels in soft ground or soft rock might be limited due to disintegration over long time or unsuitable grain size and composition.



Figure 68 : The platform wagon with containers and the temporary transfer post at the Xinma Station.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS



Figure 69 : Landscapes near the Nanao embankment after construction. The figure is simulated based on the design with an ecological pond.

8.2.2. Caopu Tunnel, Taiwan

The Caopu Tunnel, in southern Taiwan (Figure 70), is the key project to improve highway safety and transportation efficiency along the Southlink Highway, which has been in use since the 1930s. The tunnel is a twin-bore-tunnel with a total of length of 4.6km; each bore is 10.0m wide and has two lanes. The volume of rock excavated from the tunnel is 920,920 m³.

The Pacific coast in southeastern Taiwan suffers from erosion. Take the coast adjacent to the Dawu fishing port, which is northeast of the Caopu tunnel, as an example. A barrage revetment was built in 2002 to retain the coastline north of the port. This coastline banked up and moved eastward (see-side ward) at an annual rate of 2.5m to 15m between 2002 and 2008; the coastline south of the port was eroded at an annual rate of 1.7m to 2.0m (Figures 71 and 72). Therefore, using the rocks excavated from the Caopu Tunnel was considered during the project planning stage in 2009.

The stratum through which the tunnel cuts is the Chaochow Formation, formed in the middle of the Miocene epoch, and mainly consists of argillite and slate, with intercalated lenticular sandstone. Laboratory

test results indicate that the excavated rocks have moderate strength and do not contain harmful substances, suggesting that some of the large excavated rocks, excluding those with a considerable amount of clay and silt, can be used for the artificial beach.

Figure 7 shows the layout of the artificial salient jetty and off-shore dike designed to protect the coastline south of the Dawu fishing port. Figure 73 shows a typical cross-

section of the salient jetty and off-shore dike. The excavated rocks have a uniaxial compressive strength exceeding 60 MPa and a grain size exceeding 100mm; or a single rock block weighting 10 to 100 kgf can be used as backfill for the inner layer of the jetty and the dike, and those weighting between 300 to 500 kgf can be used for the cover layers. Above the cover layer, tetrapod blocks and/or cubic blocks are used to dissipate the force of incoming waves.



Figure 70 : Location of the Caopu Tunnel.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS



Figure 71 : Coastline erosion near the Dawu fishing port (left image taken in December 2000; right in June, 2005).

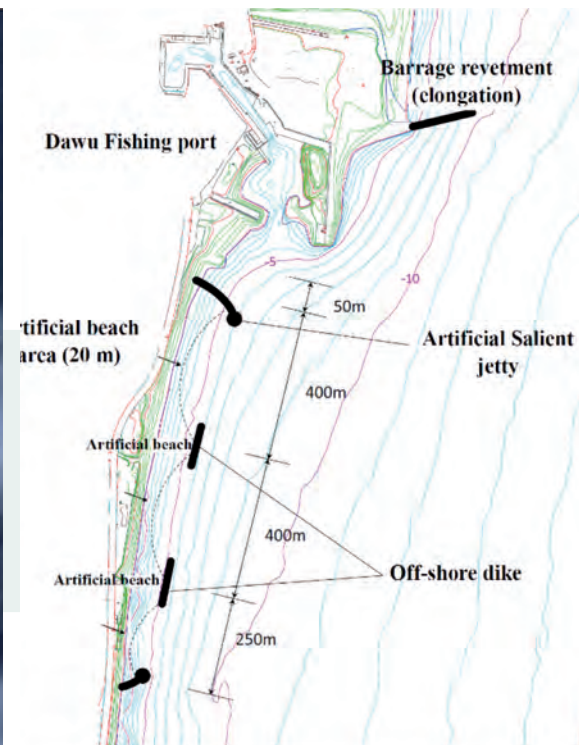


Figure 72 : Layout of the artificial salient jetty and off-shore dike designed to protect the coastline south of the Dawu fishing port.

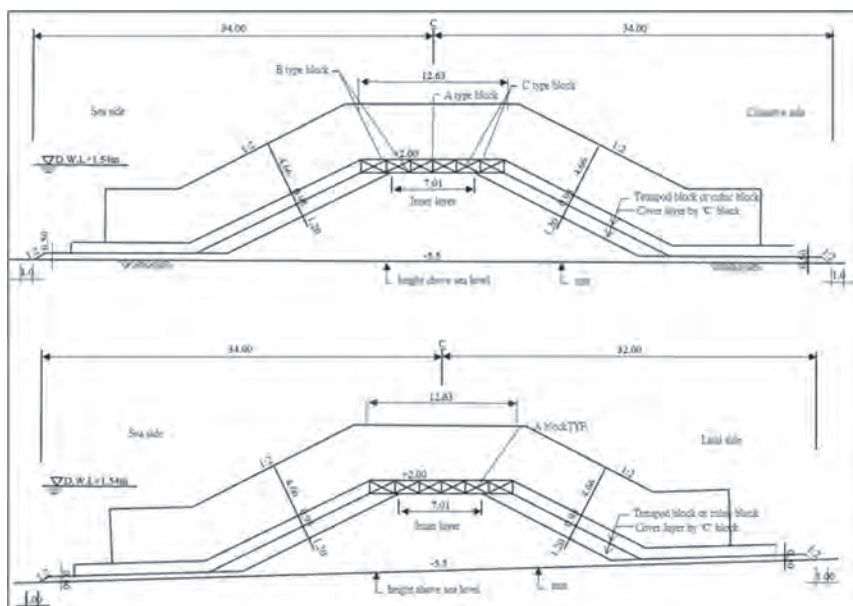


Figure 73 : Typical cross-section of the salient jetty and off-shore dike.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

8.2.3. Northside Storage Tunnel Project, Sydney, Australia

Design and Construction

The route of the main tunnel (Figure 74) commences on the western side of the Lane Cove River and extends some 16 km easterly to North Head Sewage Treatment Plant. Approximately half way along the main tunnel, a branch tunnel extends 3.5 km northerly to Scotts Creek. As part of the project, a 1.5 km spoil conveyor tunnel was constructed between North Head and Little Manly Point on Sydney Harbour.

The major controls for the vertical alignment were the deeply incised channels at the Lane Cove River, Middle Harbour and Manly. The main aim in selecting the vertical alignment (Figure 75) was to ensure that the tunnel was located in sound rock wherever possible to minimize the construction time.

At North Head separate declines were constructed to the existing underground treatment plant, to a new tunnel pumping station located approximately 100m below sea level, and to the main storage tunnel (Figure 76). The declines and caverns were excavated by three large-scale roadheader tunnelling machines. The declines were on a slope of 1:7. At the storage tunnel level a 6.6 m diameter tunnel boring machine commenced the main tunnel drive towards Middle Harbour.

A similar arrangement was adopted for the Tunks Park site where a further two large roadheaders completed excavation of the access decline and several underground caverns (Figure 77). Three tunnel boring machines operated from this site. One 3.8m diameter machine excavated the tunnel to the Lane Cove River. A second machine, 6.3 m diameter, excavated the drive towards Middle Harbour, while a third, 6.0m diameter, constructed the branch tunnel to Scotts Creek.



Figure 74 : Storage tunnel route..

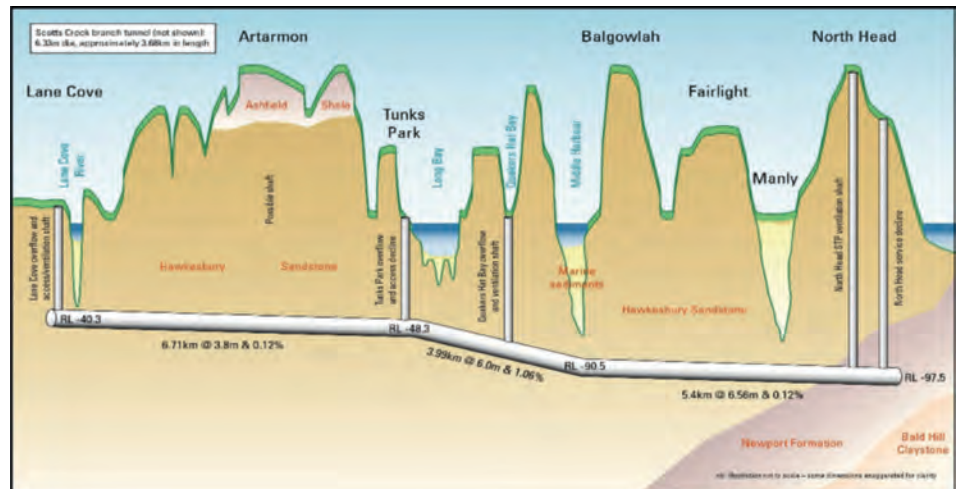


Figure 75 : Longitudinal section of main tunnel.

Removal of spoil from the tunnelling operations was a major issue on this project. Because of the location of the tunnelling works in highly developed residential areas, an alternative to spoil removal by road transport had to be found. The final arrangement entailed spoil removal from the tunnel boring machines by continuous conveyors, and removal from the underground works by

a combination of inclined, vertical and horizontal conveyors to barge loading points on the harbourside. Barges then transported the spoil some 18km across Sydney Harbour to a commercial railhead in White Bay. From there spoil was transported predominantly by rail some 45km to the western outskirts of Sydney where it was used for industrial development earthworks.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

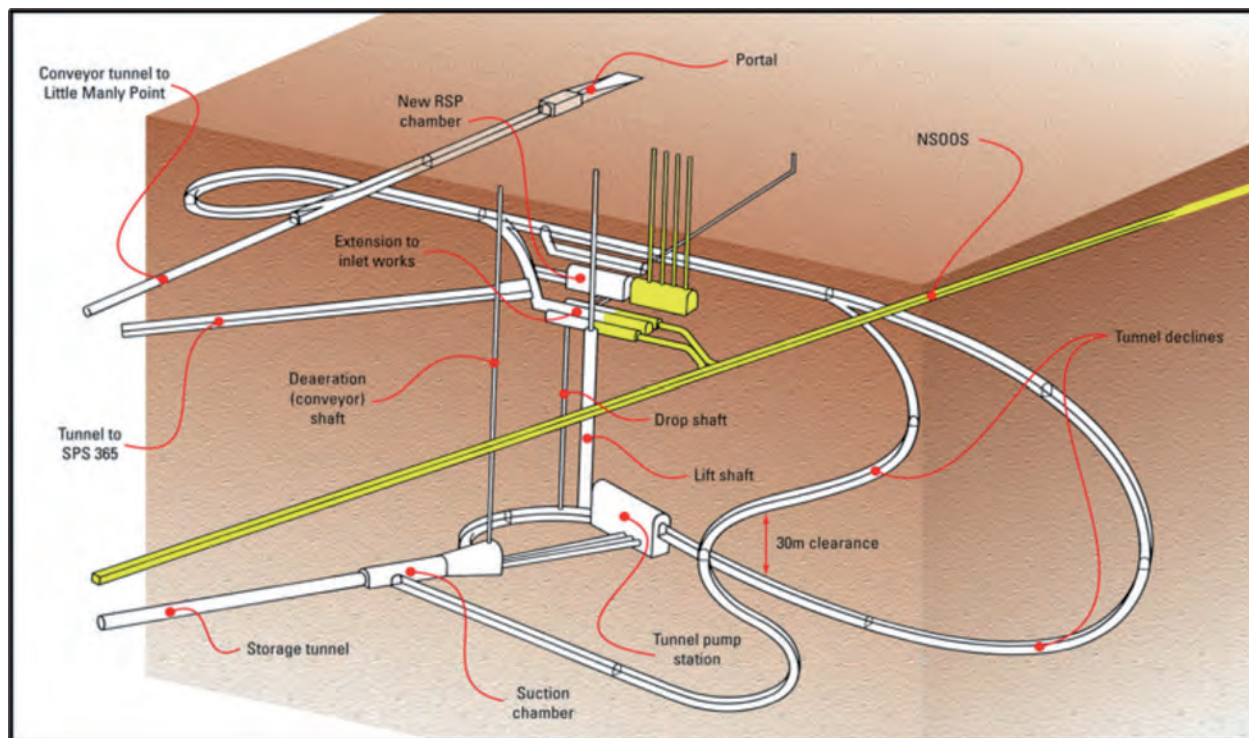


Figure 76 : North Head underground works.

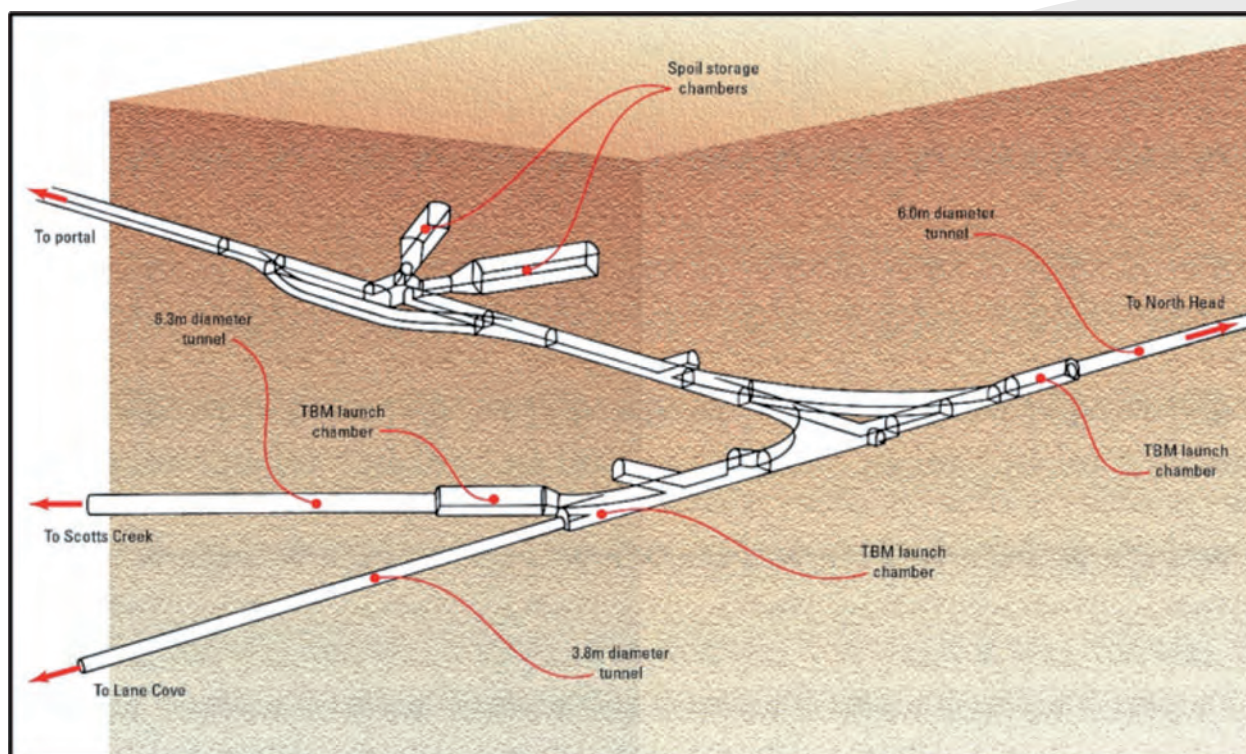


Figure 77 : Tunks Park underground works.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

One barge loading point was located at Little Manly Point Reserve in Spring Cove, North Harbour (Figure 78). Spring Cove is the habitat for Sydney Harbour's only colony of Little Penguin. Problems to be overcome at this site were the prevention of disturbance to the penguin colony and the avoidance of damage to sea grasses in the dedicated marine park area.

The Little Manly Point Reserve was also the location of a former gas works, which had been landscaped and restored as a community park. A certain amount of contaminated soil resulting from the original gas works remained on the site but was successfully stabilized in the restoration of the reserve. Construction of the spoil loading facility required removal of some of the contaminated material. Careful environmental planning was necessary to minimize disturbance of the material and avoid the risk of contaminating the highly sensitive aquatic environment surrounding the reserve.

A similar spoil handling facility was installed at the second main construction site at Tunks Park, Cammeray, within an environmentally sensitive residential area and adjacent to parkland and a public recreational reserve (Figure 79). Stringent noise and space constraints had to be overcome to allow the project to proceed.

Again, assessment of options against all objectives led to an innovative solution being reached. Two underground caverns were constructed for storage of spoil during night time and allow tunnelling to continue 24 hours per day. Offices and amenities buildings were constructed on piles over the bay and all surface workshops and barge loading facilities were totally enclosed within buildings lined with acoustic suppression cladding designed to minimize noise transmission and disturbance to the local community.



Figure 78 : Barge loading at Little Manly Point.



Figure 79 : Barge entering Tunks Park loading facility.

8 >> RECEIVED QUESTIONNAIRES AND SELECTED REFERENCE PAPERS

8.2.4. Crossrail Project, London, England

The Crossrail project in London, UK, is one of the largest infrastructure projects in Europe. The railway line is over 118km long, with 21km in tunnels with an internal diameter of 6.2m. Eight TBMs of 7.1m diameter were used to complete 10 tunnel drives of 42km of tunnels. The project also includes 12km Sprayed Concrete Lined (SCL) tunnels for construction of cross passages, station platform tunnels, access and grout tunnels.

The bored tunnels construction commenced in 2012 and completed in 2015. A total of 7 million tonnes of excavated materials from Crossrail was excavated. Approximately 98% of the excavated material from the tunnel drives and SCL tunnels were used and over half of the materials was used to create a wetland bird sanctuary, the Wallasea Island Wild Coast Project.

The excavated material from excavation of station boxes and shafts was a dry material and the material was removed by lorries and put to beneficial use, such as the creation the Ingrebourne golf course.

Barges were used to move excavated material to Wallasea by utilizing the River Thames. See Figure 80. The conveyor system that deposited the material onto the barges had magnets installed to remove the metal waste that may have been present.

Several London Underground Projects, for example the Bond Street Station Upgrade Project also sent the excavated materials from the SCL and handwork tunnels to the Wallasea Island Wild Coast Project.

During 2012-13, 180,000 tons of muck coming from Plumstead and North Woolwich were delivered to a soil grading centre at East Tilbury and were dispatched for separation into different quality grades. The larger aggregate was sold, mainly for use in the construction industry, with finer graded materials sent for use as soil in



Figure 80 : Wallasea Island – Photo courtesy of Crossrail

landfill restoration.

A huge research project has been initiated by Crossrail Ltd and Nustone Ltd in order to process the clay for Light Weight Aggregates making. The result was encouraging, good result into the lab but some difficulties with the industrial process.

8.2.5. Les Farettes, Romande Energie Hydropower Project, Switzerland

The Farettes Hydropower Project is in Switzerland within the Vaud District close to the famous Leysin ski resort area. The owner is "Romande Energie". The project will increase the power of an existing plant by 70%. It is consisting in a 5,000m long low-pressure tunnel, a shaft linking the new tunnel to the existing power plant.

The main part of the gallery has crossed a very homogenous high grade Malm Limestone which has represented 75% of the total quantity of the muck. The tunnel

has been bored by a 3.60m diameter Atlas Copco Jarva MK 12 Gripper TBM. The excavation material production has been quite regular. The grain size distribution curves are shown on Figure 81 but the muck shape was rather bad. Please see also, Figures 82 and 83.

The Malm Limestone is a very good quality raw material for concrete making, but the project concrete demand was very low, about 25,000 m³ of concrete; i.e. 50,000 tons of aggregates. After a quick and light testing campaign, it has been decided to use the EXMAT for aggregates making, without washing and with the use of only one 0/16mm class. This aggregate class coming from only a dry process screening operation was showing a rather good size distribution curve with 10% passing on the 63µm sieve, which is good for concrete and compensating for the concrete workability a low percentage of passing on the 4mm sieve. Concreting is presently on the way and the results are quite interesting and very good.

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- Concrete mix design is containing 380 kg/m³ of CEM II B(S-T) 42.5 cement with a convenient admixture content and a Water/Cement ratio of 0.50
- Workability of the concrete is in accordance with the requirements related with a pump placing and with a safe “pot life” of 2 hours
- Shuttering time, nominally 16 hours was also in accordance with the planning of the works
- Concrete strength development is also very good, over 50 N/mm² after 28 days for a C 30/37 required.

8.2.6. Gotthard Base Tunnel, Switzerland – Materials Management for 15Years

The management of the handling of approximately 25 million tonnes of spoil material from the Gotthard Base Tunnel in Switzerland was an enormous challenge. A permit system for concrete mixes and continuous testing of the excavated raw material and the grading of the broken rock ensure that as much spoil material as possible can be used to produce high-quality concretes and shotcretes for the construction of the tunnel. Although a generous margin has been applied to forecasts in materials management since the start of the project, extensive alterations were necessary to the plans and facilities for materials management to deal with the actual development of the project. The main reasons for this were changes to the schedule of material production and requirements and changes of material quantities within and between the individual sections. It has proved possible so far to avoid materials management becoming a factor holding back the performance.

When the application for the approval of the conditional project for the intermediate heading Sedrun for the Gotthard Base Tunnel (GBT) was handed in to the Swiss Federal Transport and Energy Industry Department (UVEK) in October 1994, point 3 requested for following :

«The statutory permit for construction should include the approval of the required material excavation and material storage locations as well as the required landfill sites.»

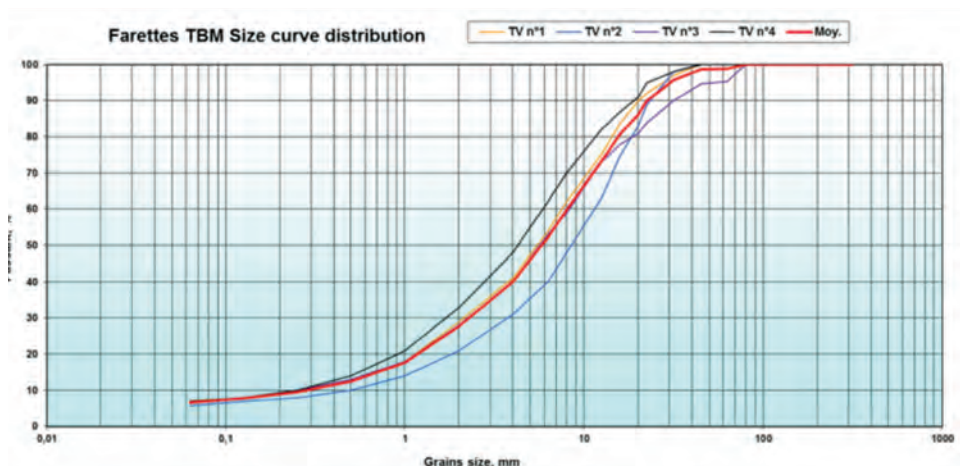
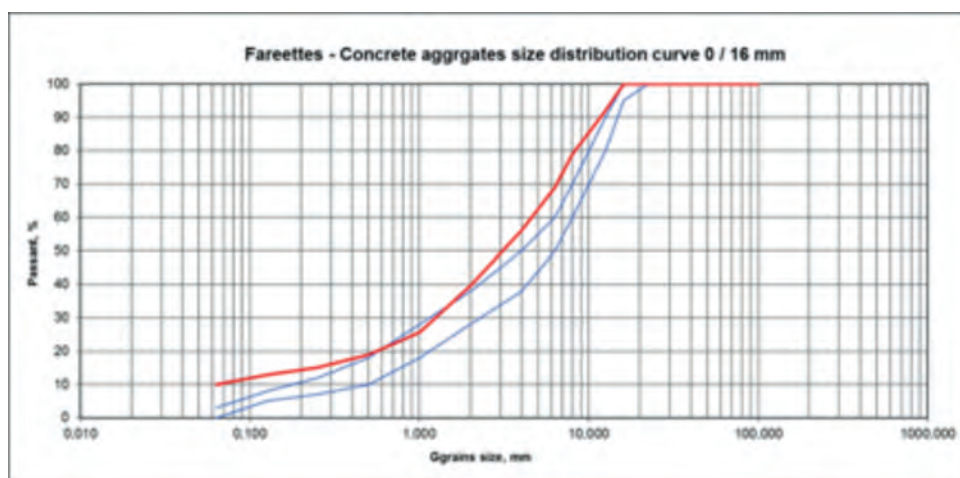


Figure 81 : Grain Sized Distribution Curve for Malm Limestone tunnel muck



Figures 82 and 83 : Left: Simple and dry treatment of the muck, right: GSD Malm Limestone tunnel muck. (Picture J. Burdin)

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The development of the project in this period has had an enormous effect on the management of materials, in addition to other influences. This discussion explains the decisive factors influencing the management of materials at the Gotthard Base Tunnel, selected important alterations and how these were dealt with. In the summary, the most significant insights are also considered under the aspect of risk management. Please see Figure 84 for an illustration of a small portion of the underground works under construction.

In the early phases of the project for the base tunnels crossing the Alps at Lötschberg and Gotthard, many technical aspects had to be overcome with little or uncertain experience to fall back on. For the management of materials handling, this concerned above all the usability of spoil materials, the influence of the high rock temperatures on quality, the required 100-year durability of the concrete and shotcrete and the subject of alkali-aggregate-reaction. The recycling of excavated material and thus the most complete possible self-sufficiency of the construction sites of the AlpTransit Gotthard AG (ATG) were a necessity; on the one hand to be able to comply with the environmental requirements, and on the other hand because the complete external supply of more than 7 million tonnes of aggregate for the production of concrete and shotcrete and the hauling away and alternative use or tipping of unused spoil material would have been impossible in some sections purely for logistical reasons.

Self-sufficiency is restrained by the minimum requirements for the mechanical and petrographical properties of the spoil material and by the time dependencies regarding material production and requirement. When enough recycled material was not available at the correct time, supply had to be organised from outside. This was above all the case in the early contract sections of the Gotthard Base Tunnel. Technical innovations were necessary to keep the quantity of recycled material as high as possible.

In the Sedrun section, mica gneiss and slate gneiss were forecast in the southern



Figure 84 : Concrete made with aggregates from TBM muck, lane change in Faido (photo AlpTransit Gotthard)

Tavetscher Zwischenmassiv, which could only be described as capable of recycling to a limited extent because of the high mica content in the fines. A technical innovation was, therefore, introduced, mica flotation to reduce the mica content in sand 0 to 1mm. This process has proved successful, and it proved possible to limit the mica content to less than 20%, even with only limited flotation (Figure 85). The basic suitability of the recycled spoil material (particularly TBM material) to produce concrete and particularly shotcrete with stringent requirements was demonstrated in a dissertation at the ETH Zürich University (Reference 14).

Recycling tests were carried-out especially for the Gotthard Base Tunnel, using Lucomagno and Leventina gneiss from the Pollmengo investigation heading and material from the rebuilding of the Amsteg Hydropower Station. A testing plan was developed for mineral aggregates from tunnel spoil material, which includes tests on the raw material and tests on the recycled aggregate.



Figure 85 : Mica extraction by flotation technique (photo C. Thalmann)

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To cope with the unusual requirements for concrete and shotcrete, an approval system was developed for concrete mixes and publicly tendered. The testing system includes the three stages suitability testing, preliminary tests under laboratory conditions and main test under construction site conditions and was also divided into the three testing sections Erstfeld/Amsteg, Sedrun and Faido/Bodio because of the different petrographical conditions along the GBT. The aim of this testing system was to reduce the risks for the client side with respect to the durability of the structure and the share of responsibility as the supplier of the aggregates.

The approval system was organised so that shotcretes and concretes could be produced with the aggregate typical for the relevant section using various concrete mixes developed by the interested bidders, and these mixes could be tested for workability as well as quality and durability. The mixes tested in this way, which were then approved with publication in the Swiss newspaper Handelsblatt, include the content of cement, additives and admixtures and are still in use today in the Gotthard Base Tunnel in an adapted form. The following tests were formulated for approval and carried out.

- Workability time: important in the damp warm climate with underground transport distances of up to almost 30 km (more than 3 hours between mixing and concreting)
- Technical requirements: compression strength, early strength, water proof quality, resistance to chemical attack
- Consideration of durability: limitation of the water/cement ratio, limit value for change of length in sulphate tests, minimum cement content

Continuous testing during construction is laid down in control plans for each contract. The subject of alkali-aggregate-reaction (AAR) has been much discussed in Switzerland since about 1996. The alkali-aggregate-reaction is primarily a chemical reaction between reactive rock particles and free alkalis in the pore water in mortar or concrete. The new product of this reaction is an expansive gel, which leads to cracks and in the worst case to the destruction of the concrete. Supported by many testing

campaigns on rock material from the area of the Gotthard Base Tunnel and inspections in various underground structures, an AAR measures concept for the GBT was developed under the leadership of the ATG. This AAR concept had to build on the existing materials management plan and the already existing concrete testing system and has the following provisions.

- Regular monitoring of the potential reactivity of the raw material and the recycling aggregate produced from it by means of microbar testing. Rejection of strongly reactive raw material before recycling.
- Testing of the AAR resistance of concrete mixes, primarily through material checks and secondarily through performance tests.
- Constructive measures to protect the concrete from water contact.

One of the most considerable challenges in materials management lies in ensuring the control of the spoil material produced and the required aggregates, even when alterations of schedule or quantity occur because of the current development of the project in contrast to the original planning. The essential factors influencing this are the suitability of the spoil for recycling and the tunnel advance rate, and the time gap between material production and material requirement.

The suitability of the spoil for recycling and the spoil quantity produced per unit of time; e.g. month, depend on the geological conditions encountered and can be subject to considerable variations in a very short time, as when an extensive fault zone is tunnelled through. For the material requirement, the planned construction schedule is decisive, whether the concreting schedule of filling embankments in the open stretches at the north and south ends. If the main concreting works for the internal structure (invert and vault) are carried-out parallel to the tunnelling work, then the daily concrete quantity and thus the requirement for aggregates are clearly lower than when the vault is constructed after the end of tunnelling work. Because shotcrete and poured concrete are mixed with different grading curves, the construction of the tunnel support in parallel with the construction of the internal vault is favourable to produce the

ingredients. The material management should not be allowed to become a factor determining the performance of tunnelling work, construction of the internal structure or filling. To achieve this is extremely difficult because of the limited space available for storing the raw material and the aggregates to buffer the individual activities.

The location of the intermediate starting point in Sedrun near the source of the Rhine influences the concept for materials management. Not only because the excavated spoil and the aggregates, like all other persons, equipment and other materials, must be transported up or down the two shafts about 800m deep, but also because the over ground route to the construction site situated about 1,400m above sea level has very limited capacities. The main road running east of Sedrun village has many curves and is so narrow in places that not even cars can always pass without problems, not to mention trucks. The railway connection on the Rhaetian railway (to Disentis), Matterhorn Gotthard railway (Disentis to the service station at Tscheppa) and the works track to the construction site is a single-track narrow-gauge line, and between Disentis and the construction site is partially rack and pinion. The non-recyclable materials, therefore, must be stored near the construction site (Figure 86).

Because, according to the forecast in the approved project, not enough spoil material capable of being recycled and reused would be available to cover needs, the construction approval from October 1995 also included the quarrying of alluvium to produce aggregates just by the village and only a few hundred metres from the portal of the access heading. The actual tunnel construction works for the Base Tunnel were in the preliminary design phase at that time. Since then, essential project has changed with a corresponding effect on materials management. The crosscut spacing was halved from 650m to 325m. The construction contract boundaries with the adjacent sections in Amsteg und Faido were altered for the construction project in 1999. A second shaft of 7m diameter was added to the originally intended shaft of almost 9 m bored diameter.

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The ventilation system in the multifunction centre was considerably extended. Because of the good progress of construction in Sedrun and the problems constructing the multifunction centre at Faido, the option provided in the construction contracts to displace the section boundary Sedrun-Faido by 1km southwards (Faido) was activated in December 2005. These major variations as well as diverse smaller excavations resulted in about an additional 900,000 tonnes of spoil, which is an increase of about 23% above the originally estimated quantity of 4 million tonnes. This results not only in more material, which would have to be tipped, but also a large quantity of spoil to be stored temporarily. The problem of temporary storage was made worse by the fact that the original project assumed the tunnel drive and the internal construction running in parallel, whereas the construction schedule according to the winning tender intended to construct the internal lining after completion of tunnelling. Measures necessary to relieve this situation included the intensive operation of the approved landfill and temporary storage sites, multiple re transporting of material, additional installations and increased expense of installation, and this all in an area where civil engineering work is normally only economic during a few months of the year.

In the gravel processing, three-shift operation had to be introduced for a while in order to be able to make sufficient aggregate available for the underground works. To further optimise the construction programme for the Gotthard Base Tunnel, negotiations were started in early 2005 for a further displacement of the section boundary from Sedrun towards Faido. A solution then had to be found for the management of the additional material produced in Sedrun. Through collaboration with all affected interested parties, councils, region and canton, residents, environmental protection organisations and planning authorities, additional landfill sites were found, which can gain approval. This meant that the materials management preconditions had been created for the decision in early 2008 to displace the section boundary Sedrun/Faido a further 1.5km southwards. This alteration produced about 750,000 tonnes of additional spoil material (Figure 87).



Figure 86 : Construction site Sedrun (photo Ø AlpTransit Gotthard)



Figure 87 : Final material deposit Buzza di Biasca (photo Ø AlpTransit Gotthard)

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There were similar challenges to be overcome in the other sections of the Gotthard Base Tunnel. At the open stretch Gotthard North and the tunnel construction contracts in Erstfeld and Amsteg, the originally intended simultaneous construction of the works proved to be impossible for political reasons and due to the legal action in the award process for the Erstfeld tunnel construction contract. Similarly, to the situation in Sedrun, the contractor's construction schedule varied from the design project. Also, worth noting is the tunnel advance in Erstfeld being considerably faster than assumed. The increase of temporary storage capacity, better installations, transport away of material and shift operation in the gravel works were also necessary here.

There were also drastic alterations in the southern part of the Gotthard Base Tunnel. In Faido, the relocation of the multifunction centre and the ventilation system which also had to be altered, produced more material in the first years, and the aggregate requirement was also greater than planned. Towards the end of the tunnel drive, the material balance will alter because of the displacement of the contract boundaries mentioned above. In the Bodio section, the suitability of the material for recycling certainly corresponded to the forecasts, but not however in terms of the times when spoil capable of being recycled and fill material were being produced. In addition, the yield of material suitable for recycling turned out to be considerably lower than anticipated due to the smaller broken size of the spoil. Both factors led to bottlenecks in the production of aggregates, which had to be remedied through additional repeat sieving, supply from the Amsteg und Erstfeld sections and the purchase of aggregates from regional quarries.

It has been necessary to work with generous margins in all areas of materials managements since the start of the project. Nonetheless, it proved necessary to undertake extensive and expensive adaptations to the concepts and facilities for the management of the spoil produced



Figure 88 : AlpTransit Public Information Center built with tunnel muck (photo © AlpTransit Gotthard)

in all sections because of the actual development of the project. So far, it has been possible to avoid the management of the materials handling becoming a factor determining the performance. This has been possible because the need for alterations was noticed at an early stage and because all parties showed very high motivation and readiness to seek solutions.

From the experience gained on this project, we can recommend the periodic reporting of performance comparisons against schedule and keeping an eye on all important assumptions in order that deviations are spotted early. Considerations of the range of scenarios and fallback policies, alternative possibilities and reserved decisions should all be included in the scope of risk management and periodically investigated. Only so can it be ensured that additional storage or transport capacity is available in good time despite long lead times for planning approval procedures and preparatory works.

8.2.7. Mechanized Tunnelling with EPB TBMs; Environmental Aspects of Soil Conditioning Process – the Approach in Italy

Tunnelling with EPB TBMs involves huge quantities of soil to be excavated and conditioned resulting in a material composed by soil and conditioning products. Depending on the national regulations, different levels of conditioning agents may be used without affecting the possibility to use (or reuse) the tunnel muck as a by-product, avoiding the extra costs of treating and handling the muck as waste material.

European regulations (European guidelines 2008/98/CE) propose a set of substances with specific limit values to be evaluated on the leachate resulting from a lixiviation test. If the values are under the limits, the muck is not considered hazardous. European regulations, however, have been defined without considering EPB muck. Surfactants, which are the main substance

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contained in TBM muck, are not considered in the European regulations, hence, there is no limit to the use of these substances.

In Italy, the approach to soil conditioning foresees at the design stage, a study of biodegradability and toxicity on the pure conditioning agent as a first step, then on the conditioned soil with a specific study which follows three steps.

- Technical study for the evaluation of the soil conditioning parameters and of the dosage of conditioning products in the tunnel muck
- Biodegradability and toxicity tests of the soil conditioned with the parameters evaluated with the technical study
- The same tests are repeated at different times on-site during tunneling operations

Biodegradability tests on the products are carried-out in accordance with OECD 310F. Toxicity tests on the products are carried-out considering different organisms.

- Mammals LD50
Toxicity on mammals (oral and cutaneous) according to OECD 401, 402, 420 or 423
- Fish LC50
According to OECD 203
- Algae IC50
According to OECD 201
- Daphnia EC50
According to OECD 202

Technical evaluation of the soil conditioning parameters and quantities are defined with laboratory tests such as slump tests, extraction tests, permeability tests, etc. The test results are conditioning parameters expressed as concentrations including the following ;

- Foam Expansion Ratio (FER)
- Foam Injection Ratio (FIR)
- Water Injection Ratio (WIR)
- Polymer Injection Ratio (PIR)

Biodegradability tests on the conditioned soil are carried-out by evaluating the quantity of surfactants in the soil, immediately after mixing with conditioning

products and at different storage times. The result is a curve showing the trend of reduction of the substance quantity in the tunnel muck. The limits for biodegradability and the organisms used for the tests depend on the specific project and/or the final destination of the muck.

Toxicity tests are carried-out on specific organisms, as a comparison between “results” (growth inhibition, mortality, etc.) on natural ground (blank value) and on conditioned ground samples over time (for example; 3 days, 7 days, etc).

The differences between Italian regulations and European regulations are quite relevant. The European regulations consider, in order to distinguish between by-products and waste, limits of a fixed set of substances for every kind of jobsite. Italian regulations on the other hand, require a detailed evaluation of the products and of the related dosage, with specific evaluation and limits specifically studied for every job site.

The Italian approach also underlines the differences between different foaming agents. The use of environmentally friendly raw materials and formulation, the absence of alcohol-based compounds and the use of specific polymers, makes a big difference in the possibility to properly treat the soil and to reduce the storage time of the soil before the final disposal; to allow the degradation of the surfactants in the soil.

8.2.8. Upgrading Tunnel Waste to Specialized Building Materials – Issues and Solutions

Greater sustainability requires increase reuse of tunnel waste in order to reduce landfill dumping and to limit the quarrying of geo-environmental resources as raw materials for the building industry. Depending on the nature of the excavated rock, tunnel muck can be used in many different ways. In case of hard rock and unreactive minerals, tunnel muck is commonly used in the production of aggregates for concrete or road base. Clay rocks and argillaceous deposits unfortunately generally require disposal

in landfills due to their poor physical properties, plastic behaviour and surfactant contamination due the excavation process through EPB TBMs.

Two studies carried-out in Italy have shown good results, both in case of hard rock used as concrete aggregate and in case of argillaceous formations used for building materials, also resolving the surfactant contamination issues from the tunnelling process (EPB TBM).

Hard rock formations, e.g. granite from the Alps in northern Italy, requires only physical treatment, such as separation, washing, grinding and size gradation or other similar operations in order to be used as concrete aggregate. In this case study, aggregate from muck was used to produce high performance concrete, matching the required mechanical strengths and maintaining the same water/cement ratio and cement dosage.

On other hand, a study carried-out in northwest Italy showed the opportunity to reuse tunnel muck from argillaceous formations, as in the case of grey clay named “Argilla a Palombini”, in order to obtain low grade binder, or Supplementary Cementitious Material (SCM) for cement replacement or raw material for cement. In this case, main benefits came from the possibility to save handling and transport costs, the essential treatment before the muck was suitable for disposal in landfills or other prescribed locations, due the presence of surfactant admixtures, as well as the saving in transport and landfill dumping costs. In the same time, this solution resulted in higher sustainability, due to the environmental preservation, reduction of greenhouse gas emissions and quarrying activities. The final focus of the study was to obtain suitable building materials, directly and rapidly inside the construction site, or close to it, through the available tunnelling clay waste.

Also, the needs of increased durability of concrete should be considered, being SCM additions frequently required in infrastructure works for this scope.

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Therefore, in this way reuse of clay waste could resolve some environmental issues, but also increase concrete durability by means cement replacement through pozzolanic SCM additions. Data from the experimentation indicates a perfect match with the international standards for SCM use in cement, or concrete. Two experimental cements containing 20% treated clay waste indicate chemical properties and mechanical strength equivalent or higher than the commercial cement today produced using fly ash, natural pozzolan and limestone in the same percentages.

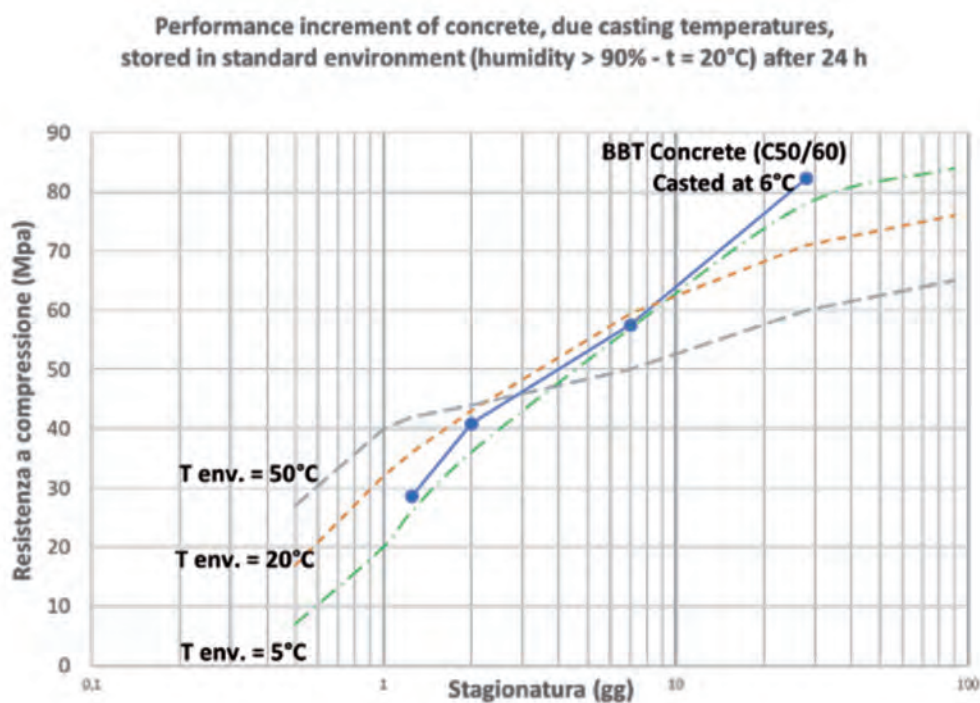


Figure 89 : Mechanical strength in concrete, using granite from Brenner Base Tunnel (BBT), in comparison of concrete containing platform limestone aggregate (Liassic), at same water/cement (w/c) ratio in different temperature of casting.

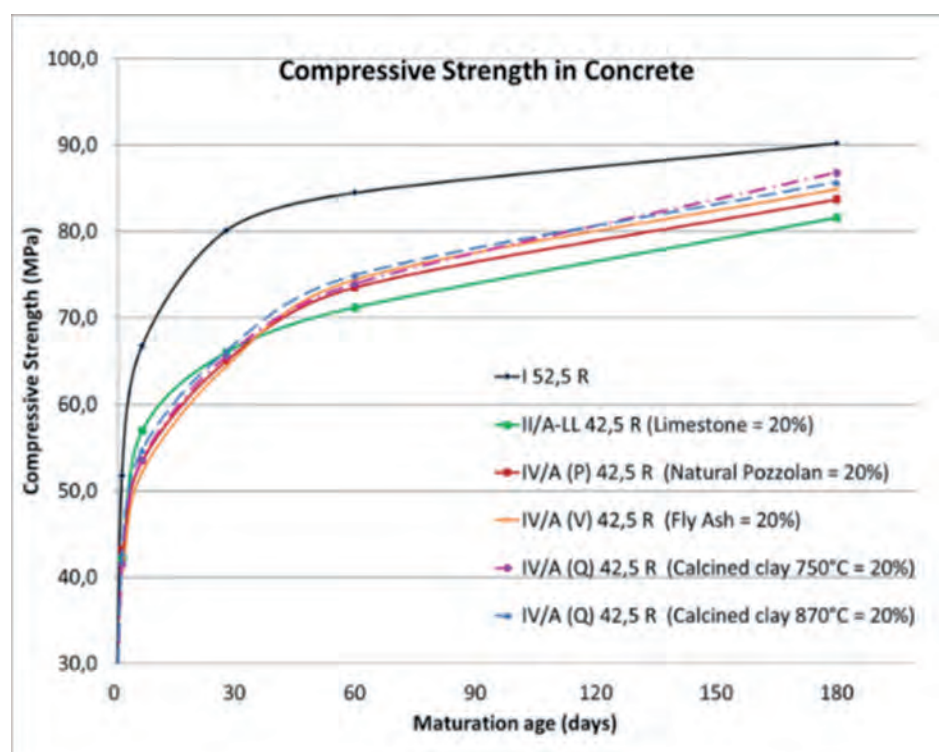
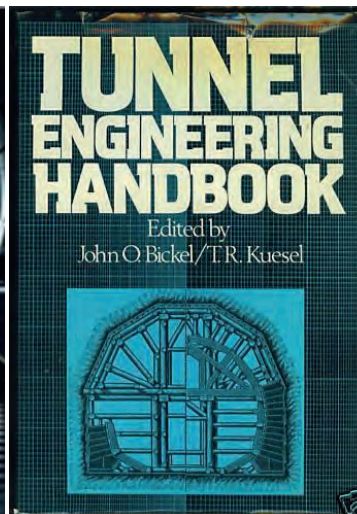


Figure 90 : Mechanical strength in concrete, at equivalent workability of two experimental blended Pozzolanic cements containing 20% of tunnelling waste, calcined at 750°C and 870°C, in comparison to the reference Portland cement Type I 52,5 R and three commercial cements containing respectively 20% of natural pozzolan, fly ash, and limestone.

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10 >> FURTHER READING MATERIALS



11 >> ENCLOSURES

11.1. QUESTIONNAIRE ITA WG 15 EXCAVATED MATERIAL /TUNNEL SPOIL

COUNTRY	
Project Name	
Project type (tunnel/rock cavern, road, railway, hydropower, etc.)	
Stage (planning, construction/operation)	
Year of construction	
Key figures	
Dimensions (length, width, cross section)	
Excavated volume (m3 solid rock)	
Geology/rock type(s)	
Excavation method (conventional drill and blast, TBM, EPB, other)	
Way of transport (vehicle, conveyor belt, other)	
Volume used in project	
Volume used elsewhere	
Volume in deposit (temporary, permanent)	
Environmental problems	
Remedial measures	
Contractual issues	
Other comments	
Illustrations and figures	

