Tunnelling in rock masses

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1 Introduction

Tunnelling is a difficult engineering discipline due to the high requirements, e. g. in terms of dimensional accuracy, watertightness, long-term stability and serviceability (service life in the order of 100 years). Extensive measurements and observations are inherent parts of the construction process. Due to the uniqueness of rock masses, each tunnelling project demands a creative strategy for planning and construction.

2 Definition and Classification of Tunnels

Tunnels are defined as expanded underground cavities with an excavated cross-section of over 20 m² and two openings to the surface. Fig. 2.1 and Fig. 2.2 illustrate the definitions of the main tunnel elements on the basis of a cross-section and a longitudinal section.

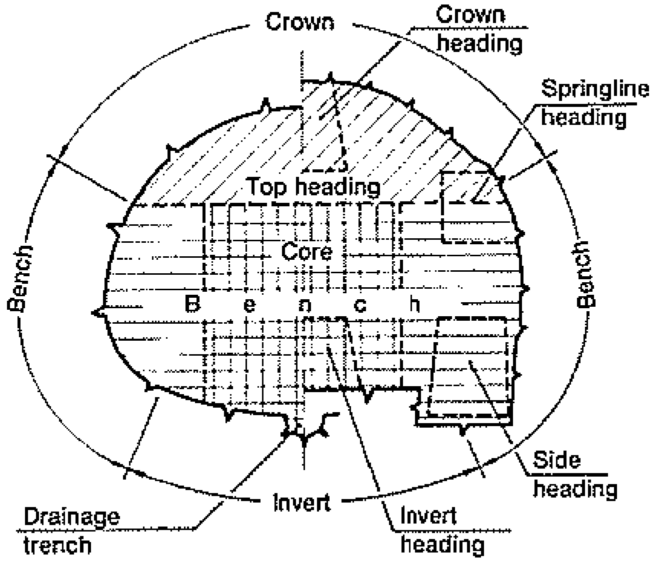


Fig. 2.1: Scheme of the tunnel components on the basis of a cross-section (Maidl, Thewes & Maidl, 2013).

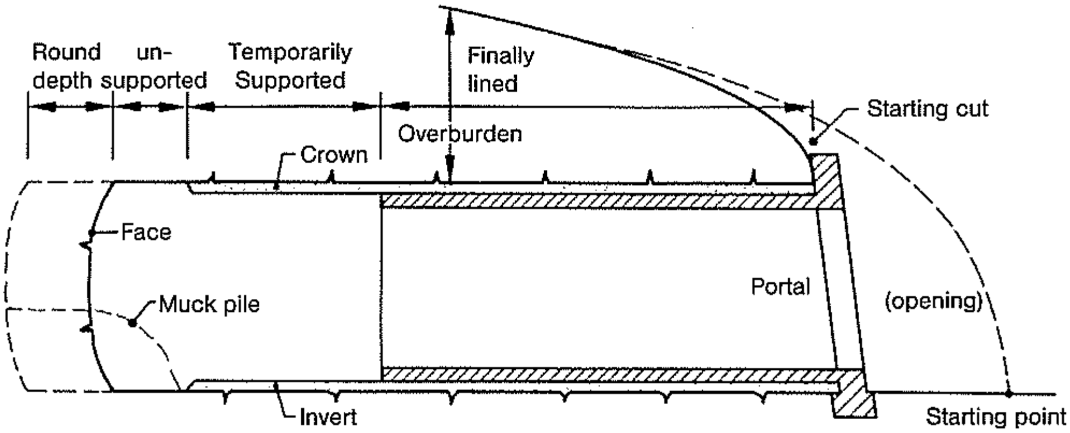


Fig. 2.2: Scheme of the tunnel components on the basis of a longitudinal section (Maidl, Thewes & Maidl, 2013).

Tab. 1: Differentiation of the types of tunnels depending on their use.

	Rail tunnels	**Metro tunnels**	**Road tunnels**
Special requirements	Aerodynamic resistance is higher => more energy needed; High velocities generate heavy barometric variation; Acceptable gradient	Increased safety requirement (high train frequency, complex route and high velocities); Waterproofing (groundwater); Air quality control; Near to the surface => lower rock strength	Special ventilation requirement (exhaust emission) => necessity of a ventilation system => high effort and costs
Reasons for tunnels	Mountains, lakes, rivers, cities	Cities, lakes and rivers in cities	Mountains, cities
Examples	Gotthard Base Tunnel; Channel Tunnel	Metro tunnels in big cities (London, Moscow, Berlin, Beijing etc.)	Gotthard Road Tunnel; Lærdal Tunnel

Depending on the utilization we differentiate between rail tunnels, metro tunnels, road tunnels, pedestrian tunnels and ship tunnels. Each of these types of tunnels has special requirements for the cross-section (see Tab. 1).

3 Geotechnical investigations

Geotechnical investigations aim at collecting all ground properties that are relevant for the tunnelling. This is necessary for technical reasons, but also for contractual regulations. Information on the underground is obtained step by step (Kolymbas, 2005):

1. preliminary investigation,
2. main ground investigation,
3. further investigation during and after construction.

3.1 Preliminary investigation

The preliminary investigation consist of

- evaluation of topographical, geological and hydrogeological maps,
- evaluation of date and experience from nearby constructions,
- site inspection to detect joints, weakness zones and conduct engineering geological mapping along tunnel alignment

The aim is to determine

- the feasibility of the planned tunnel,
- the influence of the geological situation on the excavation and
- the type and duration of further geotechnical investigations.

3.2 Main ground investigation

Main investigations are the basis for design, tendering and execution. Tab. 2 gives an overview about the most important items of the main investigation.

Tab. 2: Most important items of geotechnical investigations.

<table>
<tr><th>Necessary for</th><th>Tunnelling in Soil</th><th>Tunnelling in Rock</th></tr>
<tr><td rowspan="2">Choice of tunnelling method</td><td colspan="2">geological / tectonic situation,
homogeneous sections,
rock mass classification,
hydrological conditions,
contaminations,
gases,
drainage</td></tr>
<tr><td>structure,
bulk density,
grain size distribution,
compactness,
consistency,
water content</td><td>structure,
joints,
weathering,
mineralogical-petrographic composition,
compressive and tensile strength,
resistance to air, water and temperature,
overbreakage,
excavation sequence,
round depth</td></tr>
<tr><td rowspan="2">Dimensioning of support system</td><td colspan="2">primary state of stress,
extend of excavation disturbed zone</td></tr>
<tr><td>shear strength</td><td>tensile and shear strength,
anisotropy</td></tr>
<tr><td>Influence of excavation material and driving method to the environment</td><td colspan="2">consistency,
surface deformation,
impact on hydrogeological conditions,
vibrations,
chemical changes in case of grouting</td></tr>
</table>

3.3 *Investigations during and after construction*

The aim of geotechnical investigations during the construction is to proof the geotechnical projections during the construction phase. There are different methods to do this:

- mapping of the tunnel face and wall,
- measurements of deformation, stresses and vibrations,
- observation of the ground water.

4 Cut-and-cover and closed construction methods

Cut-and-cover and the closed construction methods are the two basic methods in tunnelling.

4.1 *Cut-and-cover construction method*

This method involves three different designs:

- Installation of the tunnel at the bottom of a construction pit and afterwards covering with filling material, see 4.1.
- Partial installation of the tunnel from the surface and underground completion afterwards, see Fig. 3.2.
- Installation of the tunnel as a caisson ashore or as a floating caisson at the bottom of shallow waters, see 4.3.

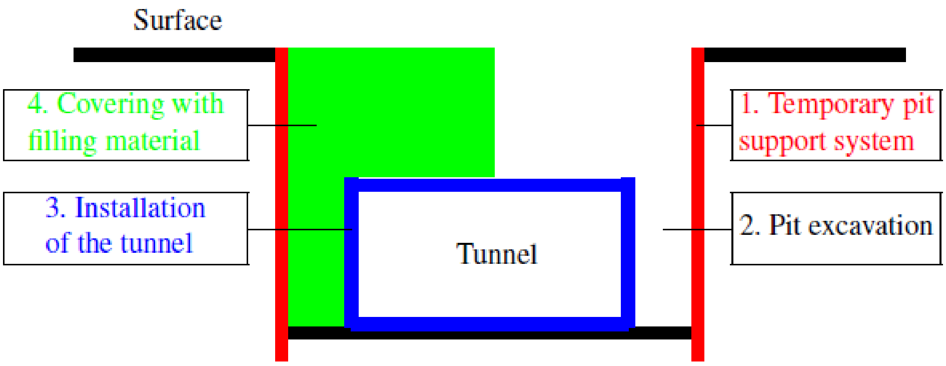
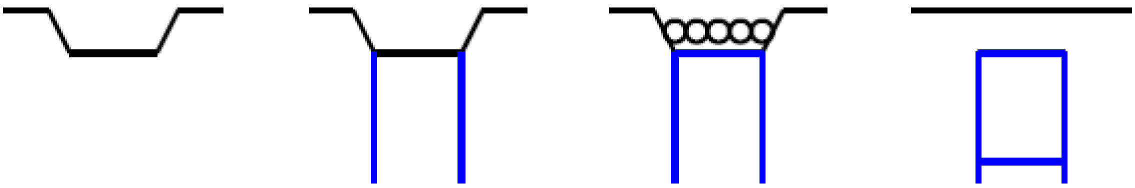


Fig. 4.1: Installation of a tunnel at the bottom of a construction pit.



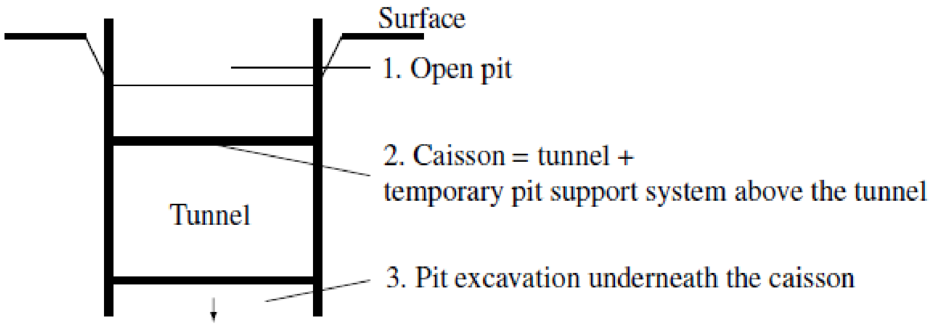
(a) Phase 1 (on surface): Excavation.

(b) Phase 2 (on surface): Installation of concrete walls.

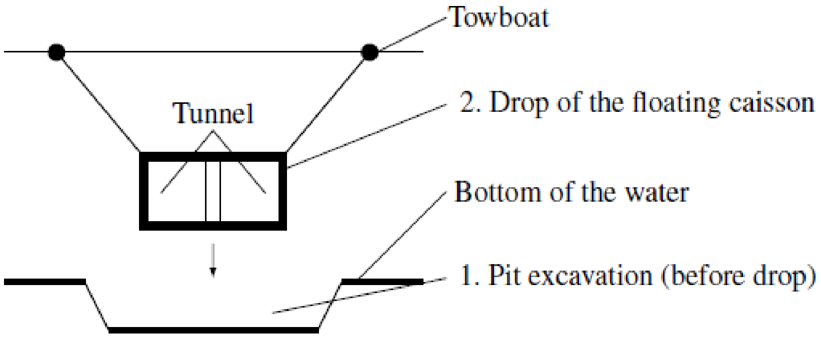
(c) Phase 3 (on surface): concrete ceiling and backfilling.

(d) Phase 4 (underground): cavity excavation and concrete invert.

Fig. 3.2: Installation of a tunnel partially from the surface with underground completion.



(a) Caisson.



(b) Floating caisson.

Fig. 4.3: Installation of a tunnel with the caisson (a) and the floating caisson (b) technique.

4.2 Closed construction method

Several techniques are available to build tunnels by the closed construction method:

- conventional excavation (drill and blast),
- shotcrete based tunnelling (New Austrian Tunnelling Method: NATM),
- conventional shield tunnelling,
- shield tunnelling with special support of the working face,
- boring technique (WSDTI, 2009).

The conventional excavation method (drill and blast), the NATM and the tunnelling with tunnel boring machines (TBM) are explained in more detail in following sections.

4.3 Limits of profitability

The cut-and-cover method is only economical until a certain depth is reached. Below that depth the closed construction method is used. The transition in respect to economy between these two methods is smooth, see 4.4. For every kind of construction the limit depth is dependent on:

- the quality of the available construction material,
- the quality and the efficiency of the applied construction equipment and
- the acquisition costs for construction materials and equipment.

The cheaper and better the quality of the construction materials and equipment available for excavating and supporting the construction pit, the greater the limit depth.

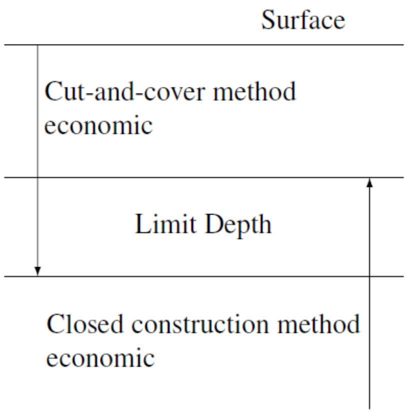


Fig. 4.4: Limit depth for cut-and-cover and closed construction method.

5 Rock mass classification for tunnelling

An overview about general rock mass classification systems is given in Abbas & Konietzky (2017). Other methods are classifications based on national norms and project-related classifications and in the first case, the classification is made with regard to the tunnelling classes. There are also standards valid for individual countries. Here we will focus on the regulations and norms valid in the German speaking regions (Germany (5.1), Switzerland (0) and Austria (5.3)).

5.1 Classification in Germany: DIN 18312

In Germany the classification for tunnel construction projects (not for mining) is regulated by the DIN 18312 VOB Part C 2002-12. This tunnel classification is a very general one and mainly based on the extent of support. According to the tunnelling method the classification distinguishes three groups given in Tab. 3, Tab. 4 and Tab. 5, respectively.

Tab. 3: General tunnelling classification for conventional tunnelling (Maidl, Thewes & Maidl, 2014).

Driving class	Type of excavation
1	Excavation without support
2	Excavation with support, in which the installation does not obstruct excavation and loading
3	Excavation with support following at a short distance behind the face, for installation: excavation and loading have to be interrupted
4 (A)	Excavation with immediately following support (division of the excavated section for reasons of stability)
5 (A)	Excavation with immediately following support including support to the face (division of the excavated section for reasons of stability)
6 (A)	Excavation with immediately following support and pre-support (division of the excavated section for reasons of stability)
7 (A)	Excavation with immediately following support including support to the face and pre-excavation support measures (division of the excavated section for reasons of stability)

Tab. 4: General tunnelling classification for tunnelling with tunnel boring machines (Maidl, Thewes & Maidl, 2014).

Driving class	Type of excavation
TBM 1	Excavation without support
TBM 2	Excavation with support, in which the installation does not obstruct the excavation
TBM 3	Excavation with support immediately behind the machine or already in the machine area, the installation does not obstruct excavation
TBM 4	Excavation with support in machine area immediately behind the cutter head, with excavation having to be interrupted to install it
TBM 5	Excavation with special measures, with excavation having to be interrupted to carry them out

Tab. 5: General tunnelling classification for tunnelling with shield machines (Maidl, Thewes & Maidl, 2014).

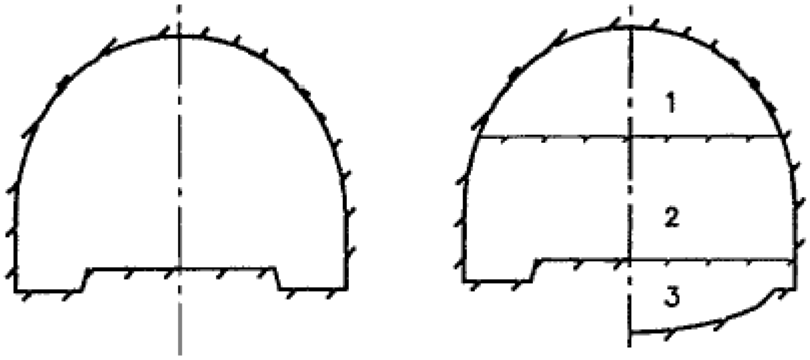
Driving class	Type of excavation
SM 1	Excavation without support to the face
SM 2	Excavation with partial support to the face
SM 3	Excavation with full support to the face

5.2 Classification in Switzerland: SIA 198

In Switzerland the classification for tunnelling projects is regulated by SIA 198. This regulation differentiates according to the type of excavation (see 5.1) and the excavation support (see Tab. 6). The result is given in a matrix of excavation type and class (see Tab. 7). There is also a differentiation according to the available tunnelling methods and the corresponding excavation types (see Tab. 8).

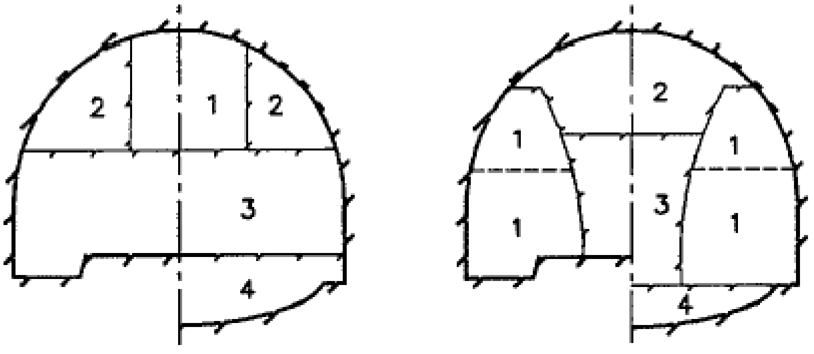
Tab. 6: Excavation classes according to SIA 198 (Maidl, Thewes & Maidl, 2014).

Excavation class	**Excavation support**
I	Excavation support causes a negligible obstruction to the excavation cycle
II	Excavation support causes a slight obstruction to the excavation cycle
III	Excavation support causes a considerable obstruction to the excavation cycle
IV	Excavation support causes an interruption to the excavation cycle (immediate support after every stage of excavation)
V	Excavation support is installed continuously with the excavation and requires immediate support to the face or a pre-support measure



(a) Full-face excavation.

(b) Top heading (1) and subsequent excavation of bench (2) and invert (3).



(c) Subdivided top heading (1, 2) and subsequent excavation of bench (3) and invert (4).

(d) Side wall drifts (1) with subsequent excavation of top heading (2), core (3) and invert (4).

Fig. 5.1: Types of excavation regarding to SIA 198 (Girmscheid, 2008).

Tab. 7: Matrix of the excavation types and classes according to SIA 198 (Maidl, Thewes & Maidl, 2014).

Excavation type	**Excavation classes**				
	I	II	III	IV	V
A Full-face excavation	A I	A II	A III	A IV	A V
B Top heading	B I	B II	B III	B IV	BV
C Divided top heading			C III	C IV	C V
D Side wall drifts			D III	D IV	D V

Tab. 8: Driving methods and corresponding excavation types.

	Rock			**Soil**	
Tunnelling method	Drill & Blast	Tunnel boring machine	Machine supported drive	Machine supported drive	Shield machine
Excavation type	A, B, C, D	A	A, B, C,D	A, B, C, D	A

5.3 Classification in Austria: ÖNorm B 2203

In Austria the classification is regulated by the ÖNorm B 2203. This norm is divided into one part for the cyclical tunnelling and another part for the continuous excavation. This classification system is based on three types of rock, characterized by the behaviour of the rock mass during the excavation (see Tab. 9).

Tab. 9: Types of rock and their typical behaviour during the excation.

Type of Rock	Behaviour
A: Rock, which basically bear the stress without fracturing	
A1 stable	Very rapidly decaying, small deformation; no detachment of rock after removing loose parts
A2 unconsolidated	Very rapidly decaying, small deformation; occasionally structure-related detachment of rock from crown and upper bench
B: Rock, which tend to softening due to lack of strength of the formation	
B1 brittle	Very rapidly decaying, small deformation; structure-related reduced strength of rock and blast vibration lead to loosening and detachment in crown and upper bench
B2 strongly brittle	Rapidly decaying deformation; structure-related low strength of rock; rapid, depth loosening and detachment of rock from free unsupported areas
B3 loose	During opening small partial cross sections of the rock trickling in;
C: Rock, in which the strength is exceeded in depth	
C1 rock burst	Sudden ravelling due to high stresses in combination with brittle rock
C2 squeezing	Pronounced, long-lasting, slowly decaying deformation; development of fracturing / plastic zones in plastic, strongly cohesive rock
C3 strongly squeezing	Big, long-lasting, slowly decaying deformation with high initial deformation rate; Development of depth fracturing and plastic zones
C4 flowing	Very low cohesion and friction; inclusion of rock even with very small, only briefly exposed and unsupported areas
C5 swelling	Kinds of rock with mineral components, which increase volume as a function of the relaxation due to absorption of water

5.4 Project-related rock mass classification in case of conventional tunnelling

Based on the tunnel classification systems mentioned above, a specific project-related classification scheme can be created for the planned tunnel. Such a classification is developed by the client as part of the planning. The main task of the geotechnical design is the economic optimization of the construction, considering the ground conditions as well as safety, long term stability, and environmental requirements (ÖGG, 2010a) A technically sound and economical design can only be achieved by applying a project and ground specific procedure (ÖGG, 2010a). The flow chart in Fig. illustrates the basic procedure of the geotechnical design process. The main parts of the geotechnical design process are the following aspects (ÖGG, 2010a):

- Determination of ground types:
    - Ground type = a geotechnically relevant ground volume, including matrix, discontinuities and tectonic structures, which is similar in mechanical properties, discontinuity characteristics and properties, rock type, rock and rock mass conditions, hydraulic properties;
    - Number of parameters is depending on the project and the design phase.
- Determination of ground behaviour:
    - Ground behaviour describes the response of the ground to the full face excavation, considering ground type and influencing factors without the influence of supports, division of face or auxiliary measures.
- Selection of construction concept:
    - An appropriate construction concept is chosen for each characteristic situation;
    - Influencing factors are ground behaviour, excavation method, spatial stress condition, ground water, subdivision of excavation cross-section, supports elements.
- Detailed determination of construction measures and evaluation of system behaviour:
    - The construction measures are designed in detail;
    - Stability of the face and the perimeter, subsequent construction steps, and boundary conditions have to be considered;
    - In most cases the construction measures have to change until a safe and economic construction method is found.
- Geotechnical report-framework plan:
    - The results of the geotechnical design have to be summarized in a geotechnical report;
    - Contents of the framework plan are:
        - Geological model (with distribution of ground types),
        - Expected system behaviour in the excavation area,
        - Criteria for construction measures,
        - Fixed excavation and support types,
        - Expected system behaviour in supported sections,
        - Warning criteria (safety management plan).

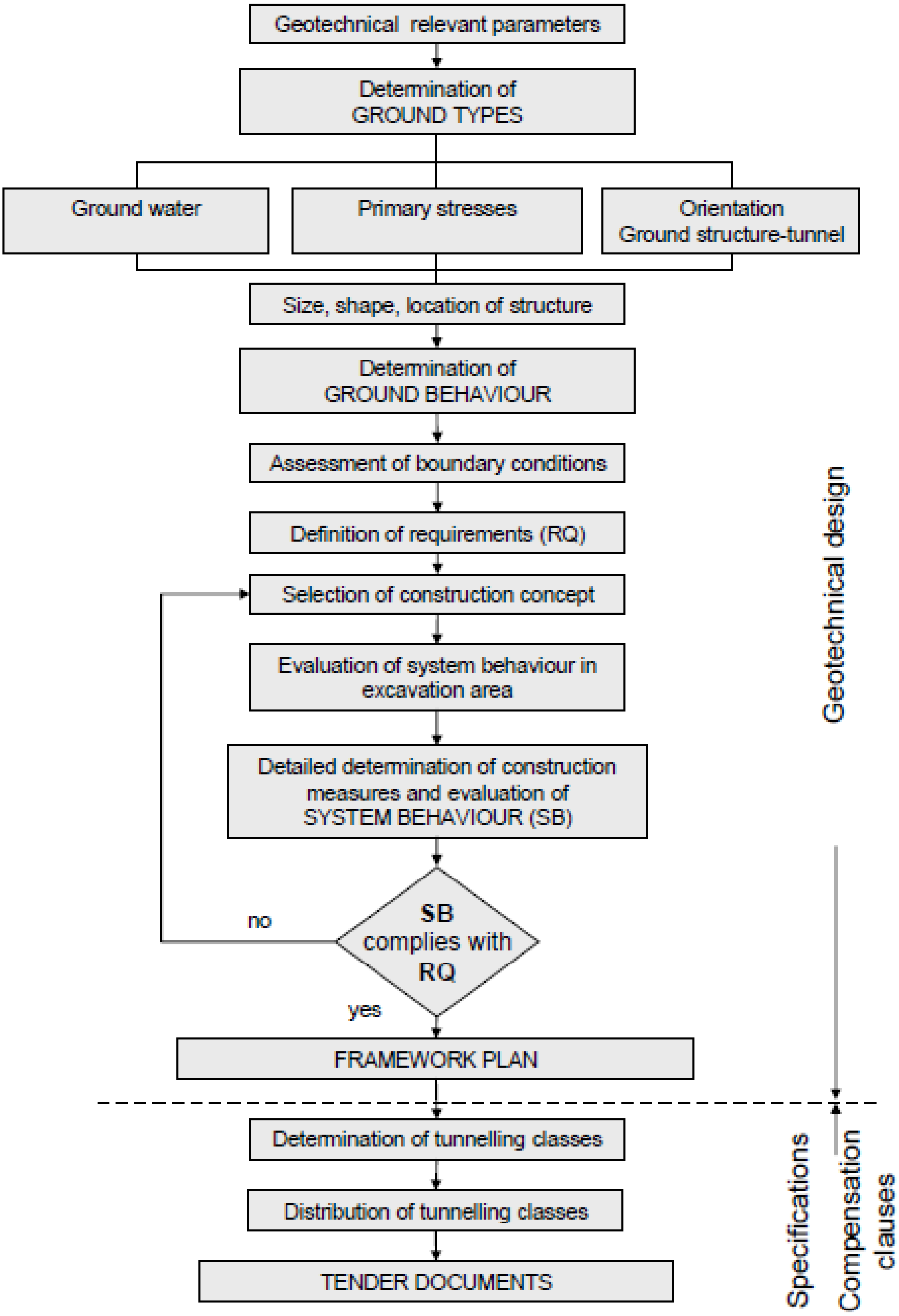


Fig. 5.2: Schematic procedure of the geotechnical design (ÖGG, 2010a).

6 Conventional Excavation – Drill and blast tunnelling

Drill and blast tunnelling can be applied almost unrestricted in stable and conditionally stable rock. This tunnelling method is very suitable for:

- hard, abrasive rock,
- non-circular or very large cross-sections and
- short tunnels.

It cannot be applied where environmental reasons (e. g. harassment by toxic smoke) or neighbouring rights issues (e. g. too close to already existing structures on the surface or underground) are reasons for the contrary. The excavation with drilling and blasting is a continuous repetition of a working cycle as shown in 6.1.

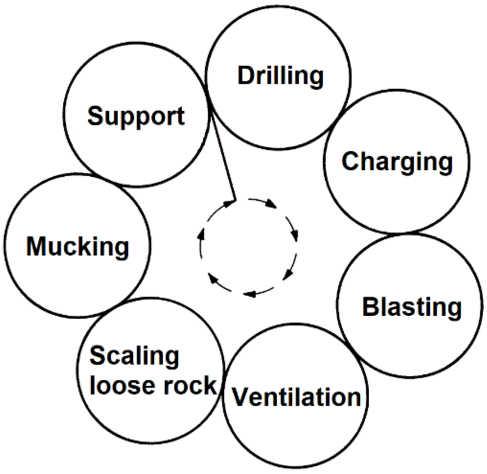


Fig. 6.1: Working cycle for drill and blast tunnelling.

6.1 Drilling

The equipment for drilling is dependent on the excavation cross section (see Tab. 10). In tunnelling, two types of cuts are used: cuts with angled or parallel holes. The most common angled cuts are the cone cut (6.1), the wedge cut (6.3) and the fan cut (6.4). An advantage of angled cuts is that less drilling accuracy is needed than with parallel cuts. Slightly inaccurate drilling can still deliver a satisfactory result (Maidl, Thewes & Maidl, 2013). Parallel cuts enable longer round lengths than angled cuts by using drilling jumbos in restricted tunnels. The most common parallel cuts are the burn cut and the parallel cut with large diameter holes.

Tab. 10: Drilling equipment according to the excavation cross section.

Excavation cross section	Drilling equipment
< 15 m²	Drilling rigs with one or two arms
15 - 50 m²	Drilling rigs with two, three or four arms
> 50 m²	Pneumatic overhead hammer drill

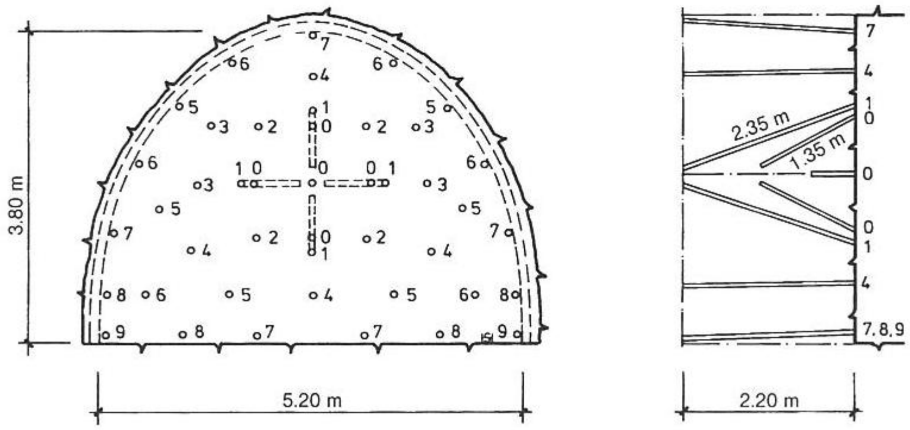


Fig. 6.2: Conical cut. The angled holes are arranged to form a conical cut. The charges are loaded near to each other at the end of the holes. They work together like one concentrated charge (Maidl, Thewes & Maidl, 2013).

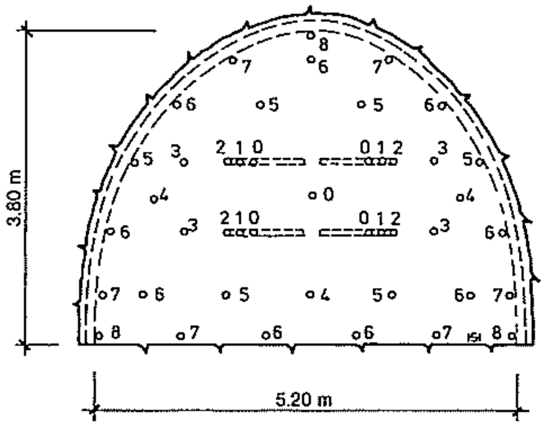


Fig. 6.3: Wedge cut. A wedge of rock is blasted from a number of vertival or horizontal opposing pairs of holes (Maidl, Thewes & Maidl, 2013).

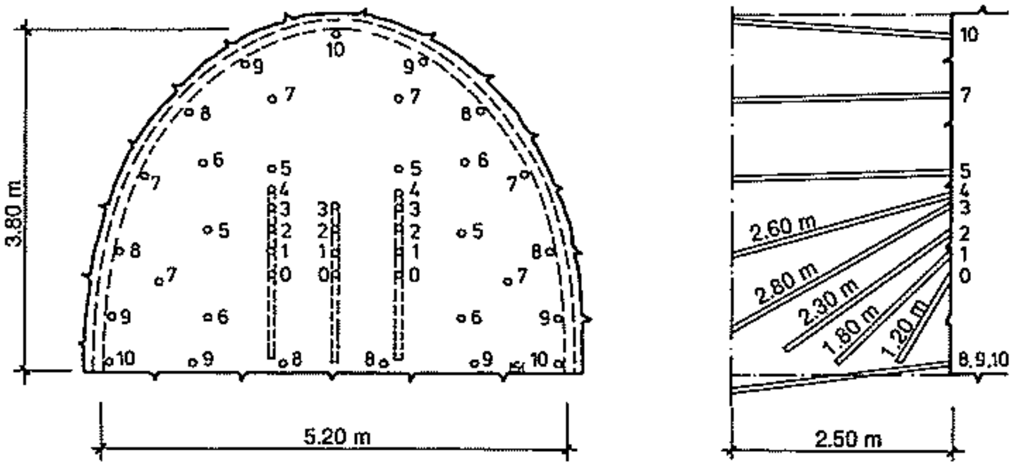


Fig. 6.4: Fan cut. The first holes are drilled at an acute angle to the face and set either vertically or horizontally with little burden. The following holes are arranged like a fan until the full round length has been reached (Maidl, Thewes & Maidl, 2013).

The round length is depending on the blasting technology, the amount of excavated material and the necessity of support. A universal calculation of the round length is not possible. One method to estimate the round length *a* is based on the excavation width and height:

$$a = \frac{d_{\text{min}}}{2}, \tag{1}$$

where d_{min} is the minimum of width and height.

The number of boreholes is depending on cross section, type of rock and kind of explosives. To calculate the number of boreholes, the following equation can be used:

$$n = c + k \cdot A_{\text{target}}, \tag{2}$$

where n is the number of boreholes, A_{target} the target excavation cross section, c and k are constants depending on the rock type (see Tab. 11).

Tab. 11: Constants for estimation of number of boreholes according to equation (2).

Type of rock	**c**	**k**
marl, mudstone, gypsum, chalk	25	0.67
sandstone, limestone, slate	31	1.00
dolomite, granite, gneiss, basalt, quartz	38	1.40

6.2 Blasting

The explosive material, which is needed for the blasting, includes explosives and detonators. Explosives can be divided into gelatine ammonium saltpeter explosives, powder-form ammonium saltpeter explosives (donarit and ammonium nitrate / fuel oil) and emulsion blasting agents.

Tab. 12: Properties and characteristics of the three different types of explosives.

Gelatine ammonium saltpeter explosives	**Powder-form ammonium saltpeter explosives**		**Emulsion blasting agents**
	Donarit	Ammonium nitrate / fuel oil	
high explosive power	strong sliding effect on rock	sliding effect and low rate of detonation	very good detonation behaviour
good weather resistance and handling safety	sensitive to moisture and can only be stored for a certain time	lose its detonability when wet or compacted, extremely safe to handle	good storage stability, extremely safe to handle
mainly used in hard rock	used in tunnelling only to a limited extent, depending on rock properties, mainly in soft rock	rarely used in tunnelling	very well suited for tunnelling

Tab. 13: Consumption (in kg/m^3) of explosives depending on cross-section and rock type (Maidl, 1997).

Rock type	**Cross-sections up to**		
	6 m^3	**10 m^3**	**40 m^3**
Soft rock (e.g. marl, clay, silt)	0.8 – 1.5	0.6 – 1.3	0.3 – 1.0
	Donarit		
Medium-hard rock (e.g. sandstone, limestone, slate)	2.0 – 2.8	2.0 – 2.5	1.2 – 1.7
	Gelatine ammonium saltpeter explosives, Emulsion blasting agents		
Hard rock (e.g. hard limestone, dolomite, granite)	2.5 – 3.5	2.5 – 3.0	1.5 – 2.0
	Gelatine ammonium saltpeter explosives, Emulsion blasting agents		
Very hard rock (e.g. hard granite, gneiss, basalt)	2.8 – 3.8	3.0 – 3.5	2.0 – 2.5
	Gelatine ammonium saltpeter explosives, Emulsion blasting agents		

6.3 Ventilation during the construction phase

Sufficient fresh air must be available at all workplaces underground. The oxygen concentration of the air is reduced by breathing, combustion and the addition of other gases and therefore has to be supplemented. Different ventilation methods are available. The most common types are positive pressure ventilation (6.5), extraction ventilation (6.6) and combined ventilation (6.7).

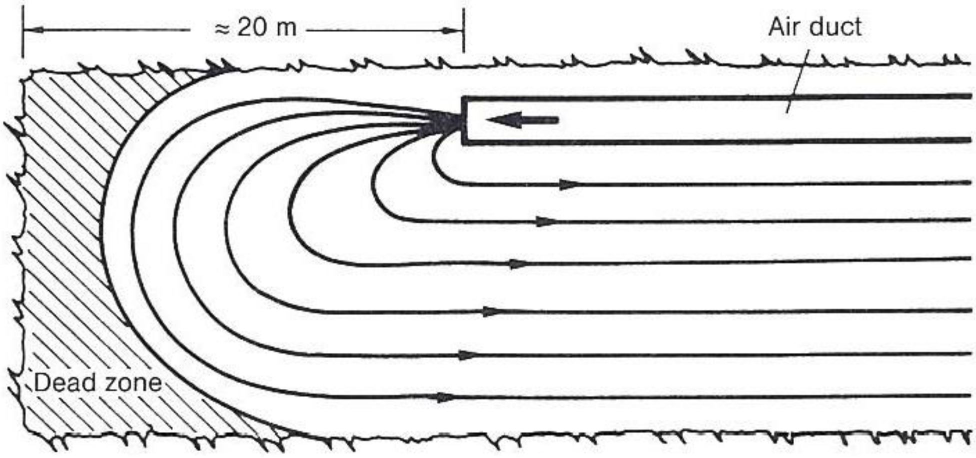


Fig. 6.5: Positive pressure ventilation. A fan sucks in fresh air and feeds it through a duct to the underground workplace (Maidl, Thewes & Maidl, 2013).

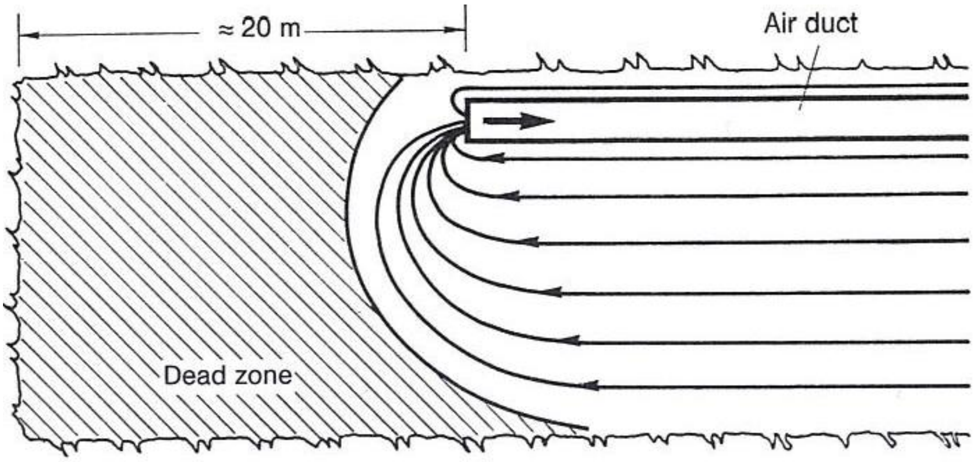


Fig. 6.6: Extraction ventilation. The contaminated air is extracted through the working place and blown out of the tunnel through a duct, and then replaced by fresh air flowing through the tunnel (Maidl, Thewes & Maidl, 2013).

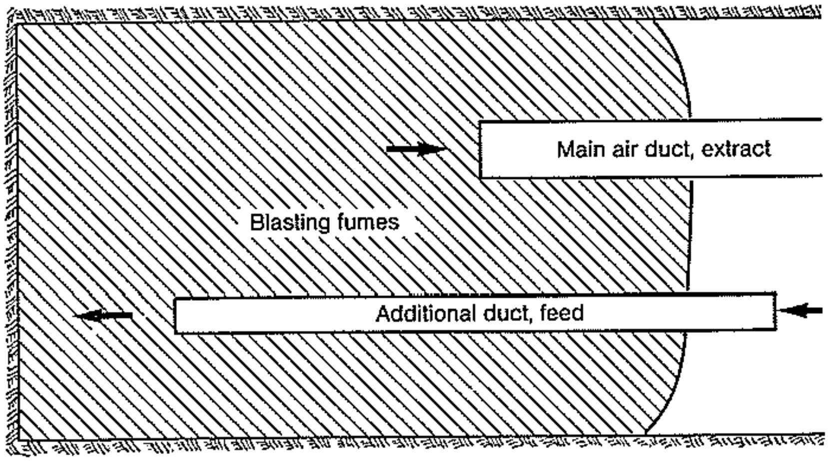


Fig. 6.7: Combined ventilation. Extraction ventilation is only practical when used in combination with a supplementary positive pressure air feed, which feeds clean air to the tunnel and blows against the face (Maidl, Thewes & Maidl, 2013).

6.4 Mucking

Mucking means the transportation of the material thrown out by blasting away from the face. This process can be divided into loading and transportation. A thorough planning of this process is essential, as it has a huge impact on the construction time. The performance of loading and transportation has to be optimized. Essential criteria are (Maidl, Thewes & Maidl, 2013):

- available clearance in cross- and longitudinal section,
- transportation distance,
- gradients,
- excavation quantities per excavation cross-section,
- characteristics of the excavated material.

An overview of the available loading and transportation equipment is given in Fig. 6.8 and Fig. 6.9. For economic reasons, the mucking must be done as soon as possible. Therefore, an optimal utilization of loading machine is required and the number of transportation units based on it.

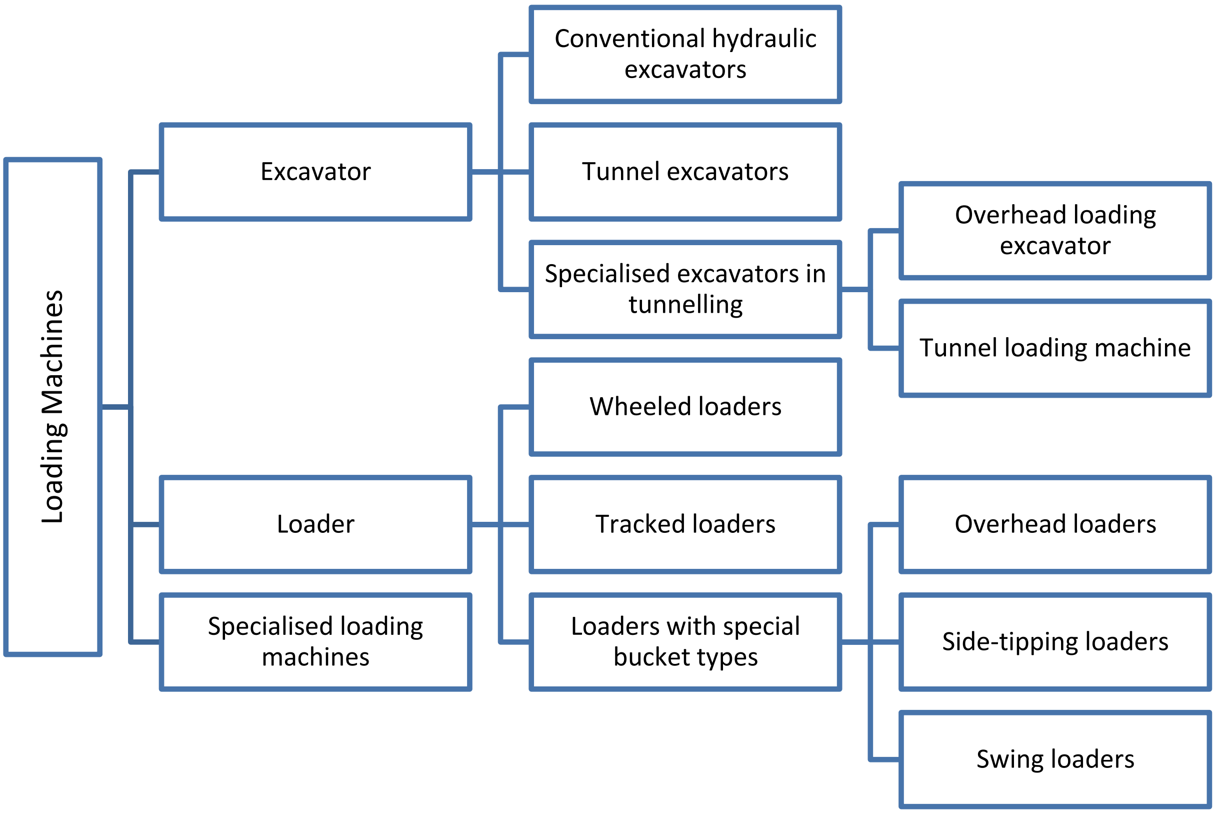


Fig. 6.8: Overview of the loading machines.

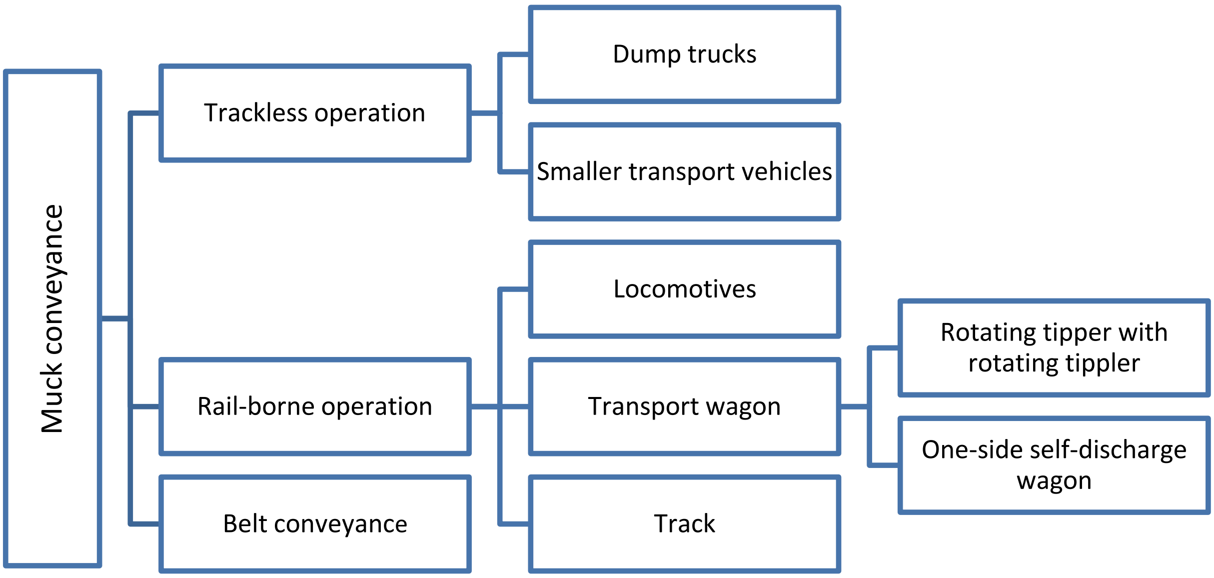


Fig. 6.9: Overview of the muck conveyance.

7 Tunnel boring machines

Tunnel boring machines (TBM's) can excavate the required cross-sections by mechanical release of the rock with a relatively accurate profile. TBM's either excavate the entire tunnel cross-section with a cutter head or cutting wheel or partial sections using appropriate excavation equipment (DAUB, 2010).

7.1 Categorisation of tunnelling machines

Tunnelling machines (TVM's) can be divided in four groups, see Fig. 7.1.

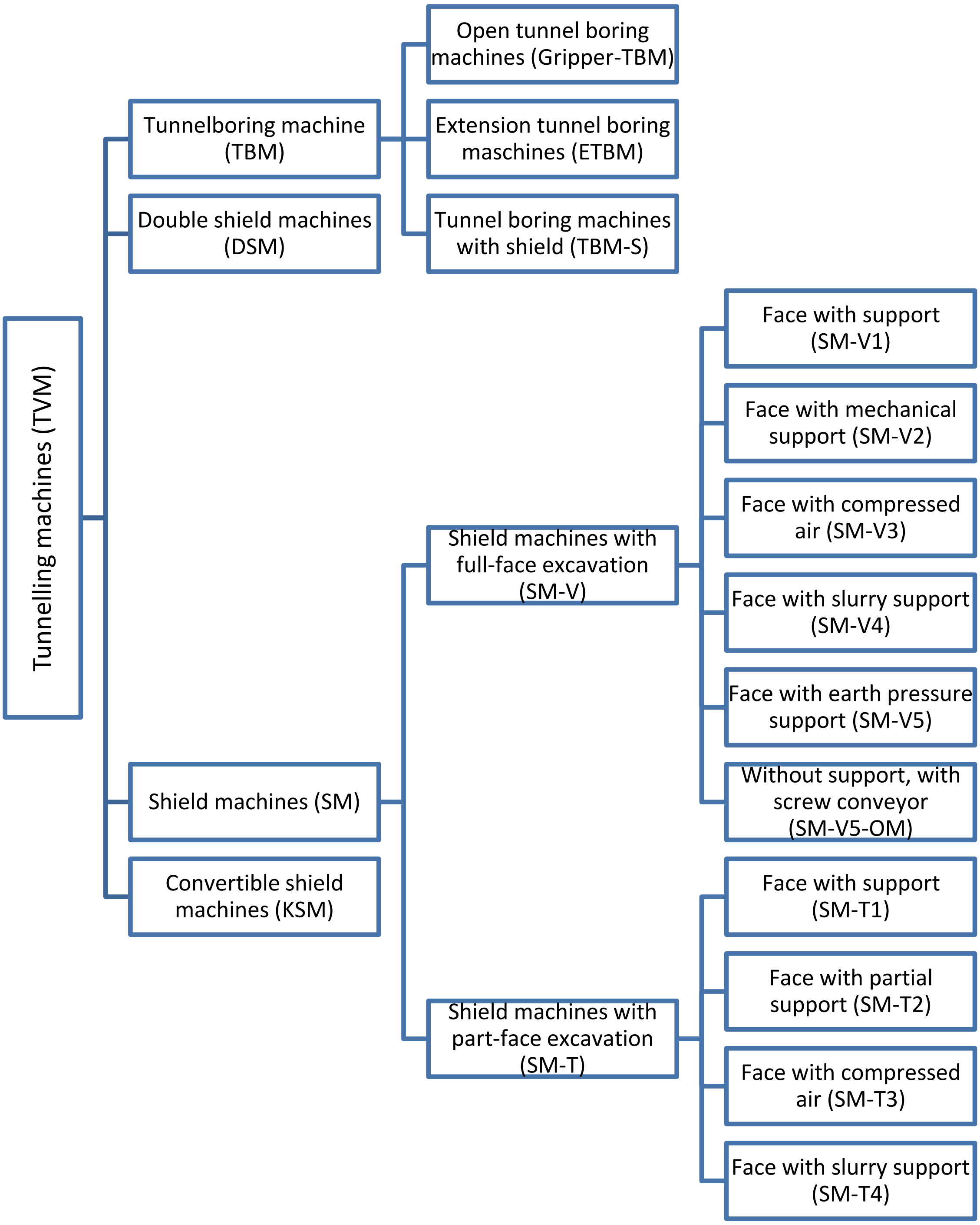


Fig. 7.1: Categorisation of tunnelling machines (DAUB, 2010).

In this chapter, we will focus on the tunnel boring machines (TBM's). These machines are used for the excavation in stable hard rock. It is not necessary to support the face actively. Generally a TBM can only excavate circular cross-sections. TBM's can be further subdivided into three groups: machines without shield skin (gripper TBM's), enlargement tunnel boring machines and tunnel boring machines with shield skin. A gripper TBM (see Fig.) is used in hard rock with medium to long stand-up time (DAUB, 2010).

7.2 Criteria for use of TBM's

TBM's can be used in all types of rock, but they are most advantageous in stable and conditionally stable rock masses. The possibility of using them is depending on the geology, (see Fig. 7.2) economic factors are also important to consider. The profitability of a tunnelling machine depends essentially on the tunnel length, see Fig. 7.3.

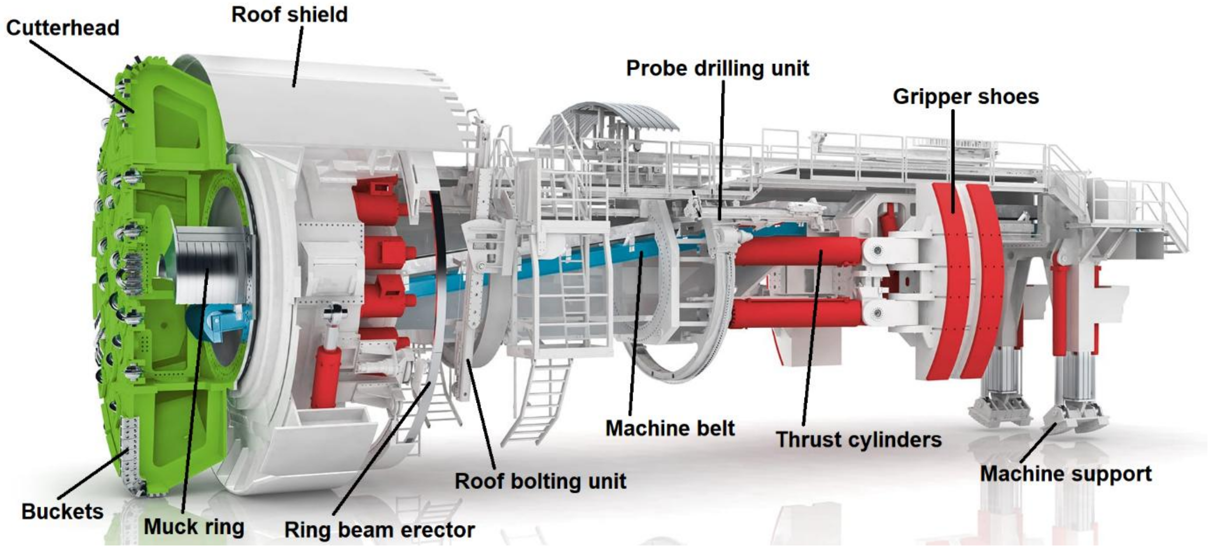


Fig. 7.2: Elements of a gripper-TBM (Herrenknecht Tunnelling Systems).

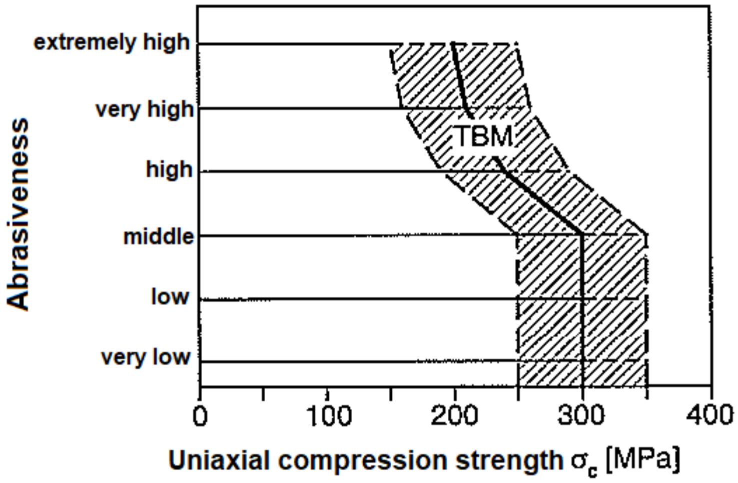


Fig. 7.3: Range of application of a TBM depending on compressive strength and abrasiveness (Girmscheid, 2008).

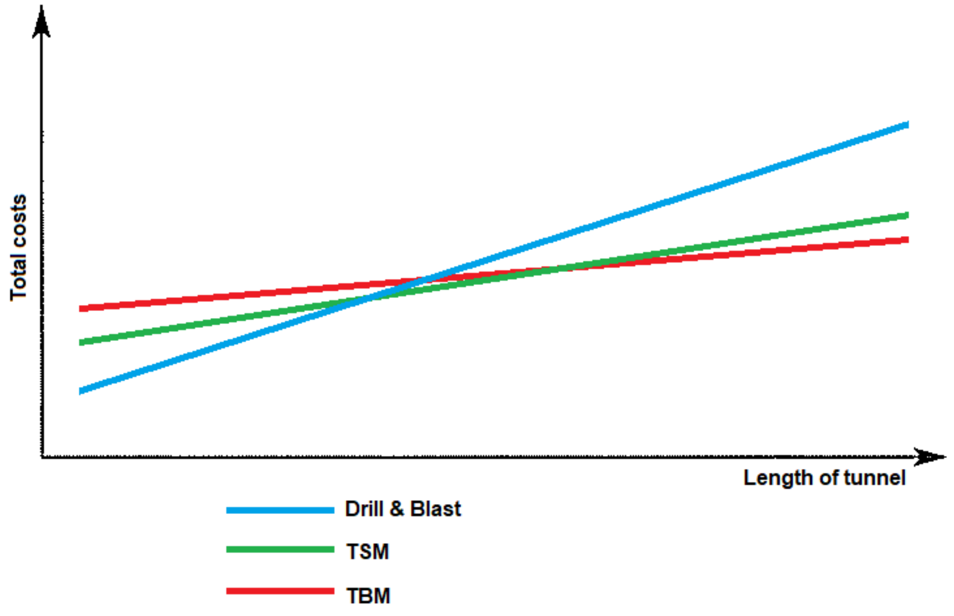


Fig. 7.4: Total costs versus tunnel length for different tunnelling techniques.

7.3 *Advantages and disadvantages of TBM*

The advantages of a TBM are:

- Reduction of necessary support;
- Control and reduction of overbreak, which leads to preservation of stability and increase of stand-up time;
- Statically favourable profile design, elimination of stress concentrations;
- Shorter construction times, reduction of costs for maintenance as well as construction related costs;
- Facilitation of work (personnel savings, better working conditions).

The disadvantages are:

- Reduction of excavation velocity when encountering weak zones;
- No immediate measurements possible (only behind the machine);
- Water entry can lead to malfunctions (silting of the machine);
- Generally only circular cross-sections, thus overprofile;
- High initial costs (amortization only for longer tunnels);
- Long delivery time for the machine;
- Detailed explorations necessary because changes later on only hardly manageable.

7.4 Deformable lining segments

Squeezing rock masses can produce extreme large loadings on the lining segments. These loadings can exceed the load capacity of the lining segments. In these cases deformable lining segments (Fig. 7.5 and 7.6) can be used.

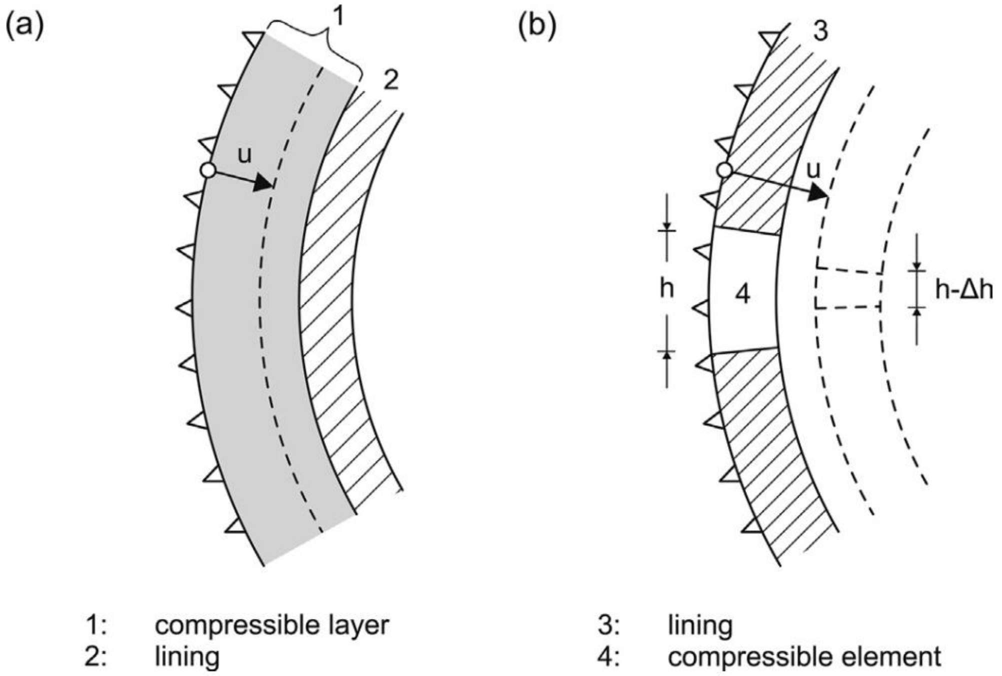


Fig. 7.5: Principles of deformable lining segments (a) radial deformation, (b) tangential deformation (Mezger, F. et al. 2018)

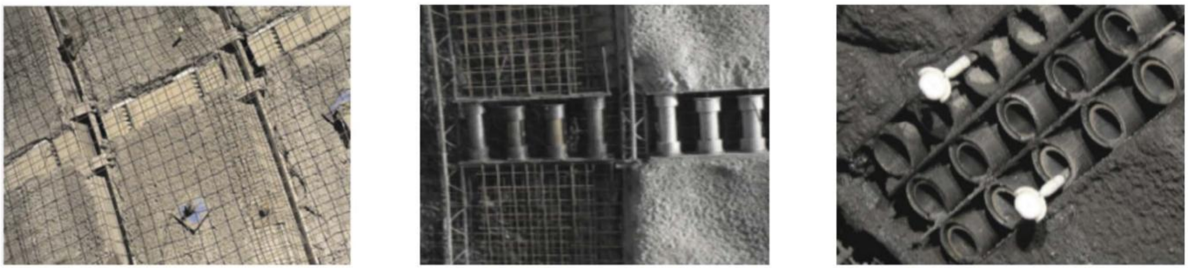


Fig. 7.6: Fotos of different types of lining segments (a) radial deformation, (b) tangential deformation (Mezger, F. et al. 2018)

8 New Austrian Tunnelling Method

The New Austrian Tunnelling Method (NATM) is based on the activation of a rock support ring, through which the rock around the cavity becomes a load-bearing component. The following aspects must be considered:

- Consideration of geomechanical rock behaviour;
- Avoidance of unfavourable stresses and deformations by timely installation of support measures;
- Timely bottom closure to complete the rock support ring;
- Optimization of the support resistance as a function of the permissible deformations;
- Geotechnical monitoring for control and optimization.

There are 21 basic principles as stated by Leopold Müller, see Maidl, Thewes & Maidl (2013) or Adam (2016). For example, the construction procedure can be subdivided into six phases (Fig. 8.1):

1. The tunnelling starts with excavation of the top heading. The round lengths are small, so only a narrow strip is exposed at the top heading circumference. The core supports the face against displacements into the direction of the cavity.
2. To preserve this relatively stable state, a shotcrete layer is applied to the exposed arch as quickly as possible. The result is a thin horseshoe-shaped arch.
3. Protected by the arch the core is removed up to the height of the rein.
4. Excavation analogous to phase 1, see Fig. 8.1.
5. Completion of the shotcrete arch in analogy to phase 2.
6. Phases 4 and 5 now allow the excavation of the rest of the core. The arch, which is still open at the bottom, is completed after the excavation of the core by the application of an invert arch. A completely closed arch develops much greater resistance than an invert-open arch. Therefore, the closure process has to be finished as quick as possible.

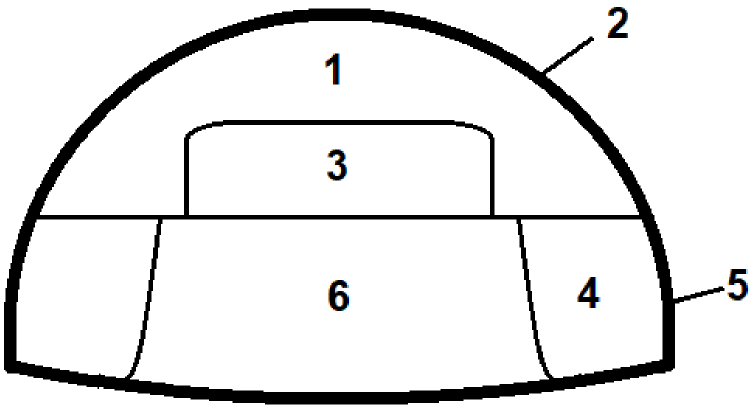


Fig. 8.1: Excavation phases in NATM.

Starting in phase 2, both the deformation of the shotcrete and the deformation of the rock in the cavity environment are observed and evaluated for all working steps by suitable measuring devices. This results in plans for the immediately following working steps on site as well as for the most favourable time of insertion and the design of the final facing. For this final facing, shotcrete, anchors, steel arches and structural steel meshes are used. These types of support can be used very early on and can be adapted to changing rock properties and varying excavation cross-sections.

Fig. 8.2 shows different variations of the staggering of the face, which was initially common in the excavation of large cavity cross-sections in the NATM. For a long time, the practical advantage of such a staggering was seen in the need to react to changeable geological-geomechanical conditions by changes in the round length and / or the excavation measures exclusively. On the other hand, the excavation cross-section and working rhythm could still be kept unchanged, thus ensuring a continuous utilization of tunnelling teams and equipment. From a multiple staggering of the face be a static problem arises in brittle rock. Thus, the initial horseshoe-shaped shotcrete vault initially in the face area should be completed as quickly as possible by concreting the invert to a closed tube, because the ring closure time has an essential effect on the rock behaviour. Given that the face can be adequately supported, a quick bottom closure is the most effective way to reduce surface settlement. To obtain longer dwell times of the rock and close the bottom of the vault at a later time, a lengthwise development was sought, allowing the simultaneous use of more personnel and equipment. Today this contradiction between geomechanical findings and constructional-organizational issues is countered in the NATM through the transition from the horseshoe cross-section shown in Fig. 8.2, which is gradually increasing, but still open, to self-contained partial excavations with circular or elliptical cross-sections.

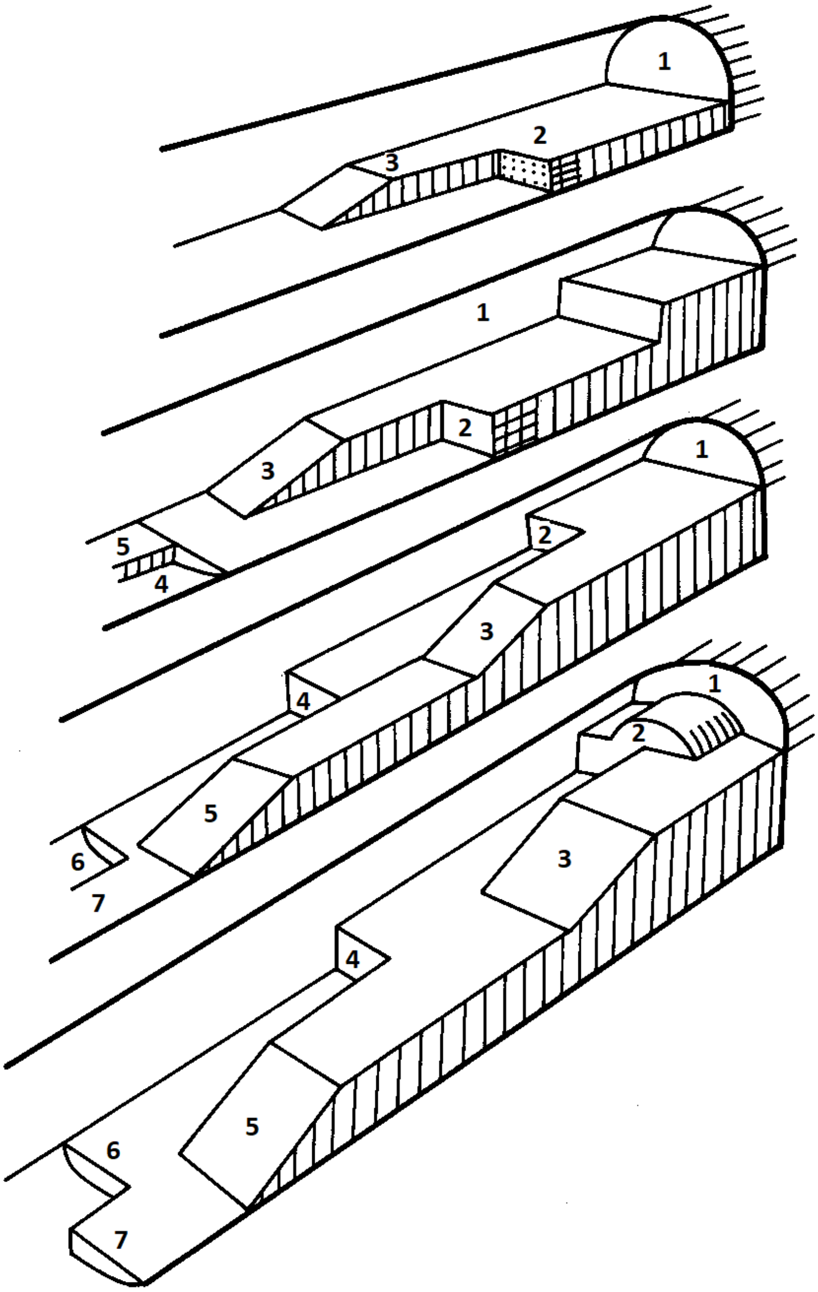
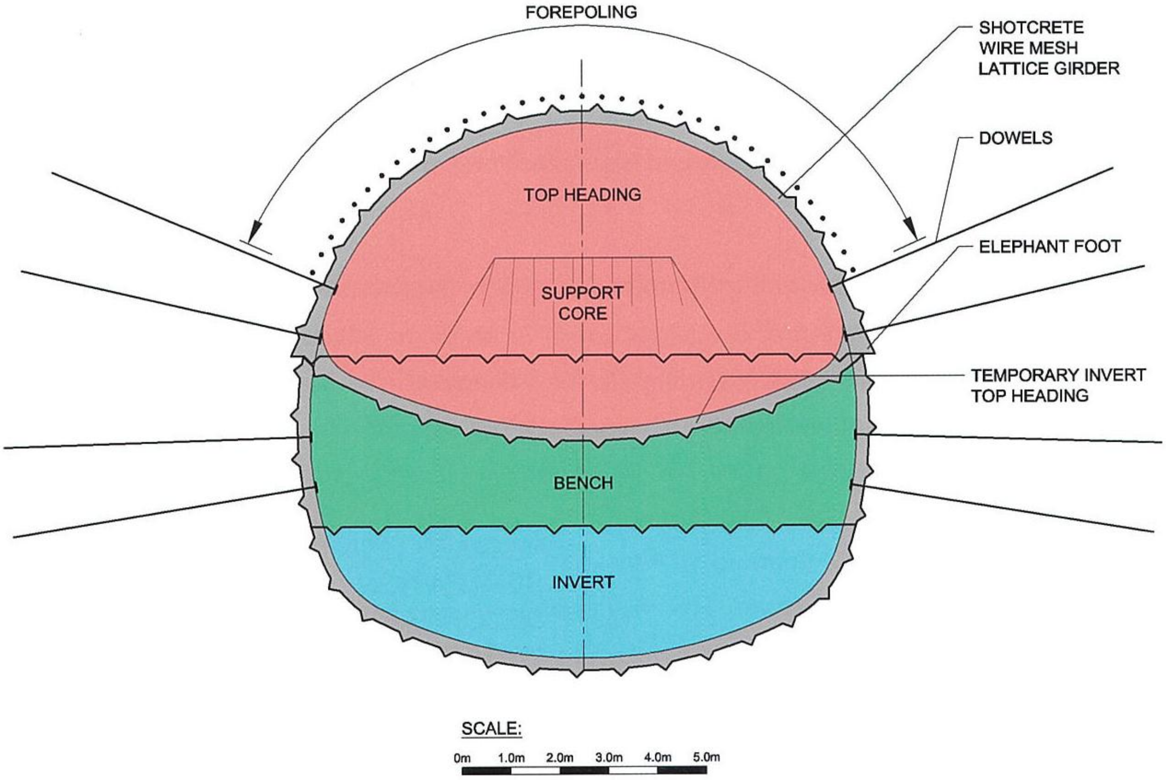


Fig. 8.2: Different variants of staggering the face (NATM).

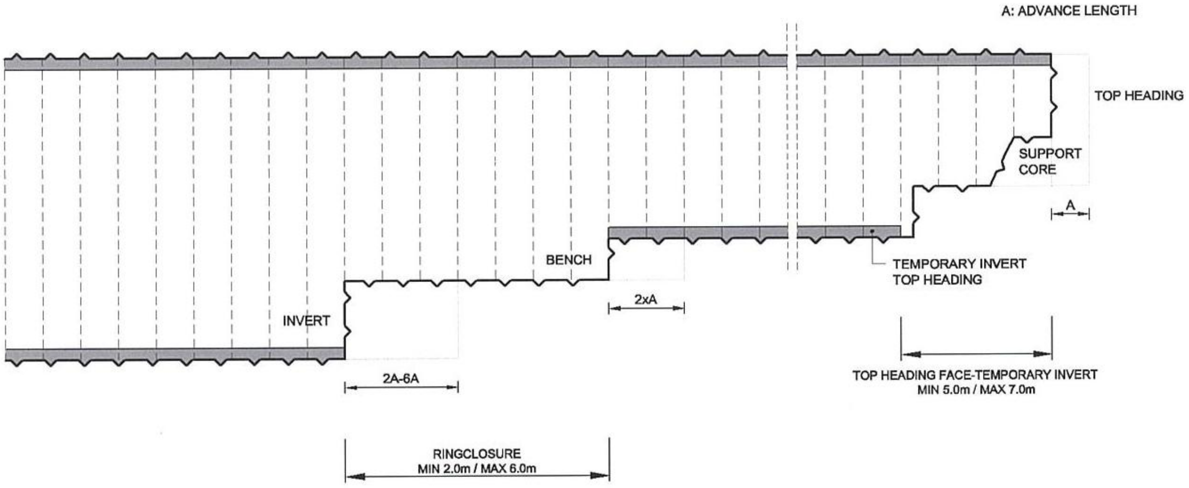
The procedures currently in use in the NATM, with the help of partial excavations with continuously curved contours to realize the definitely required excavation cross-section, can be attributed to the two basic variants:

- Top heading-bench-drive (Fig. 8.3) and
- Side wall drift method (Fig. 8.4).

These two basic variants are varied in many ways, depending on the local geological-geomechanical conditions.

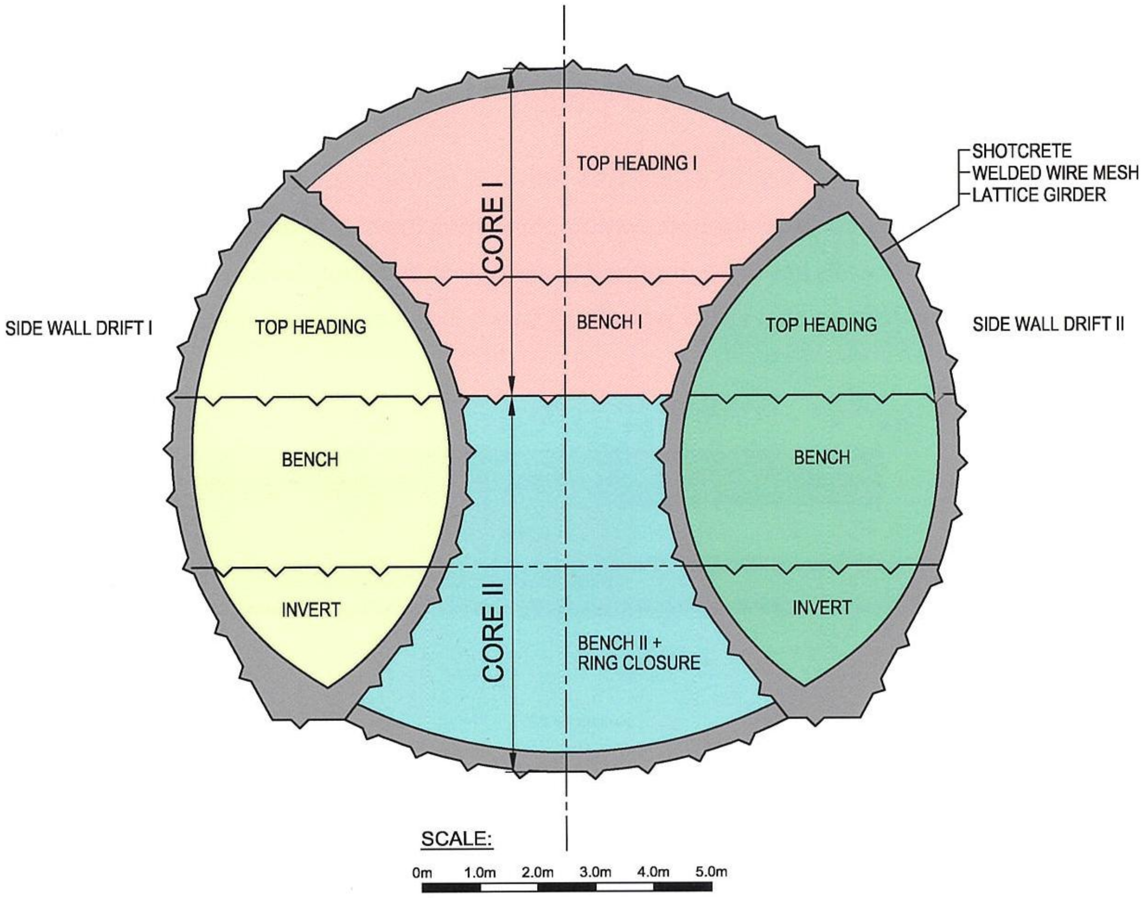


(a) Excavation and support.

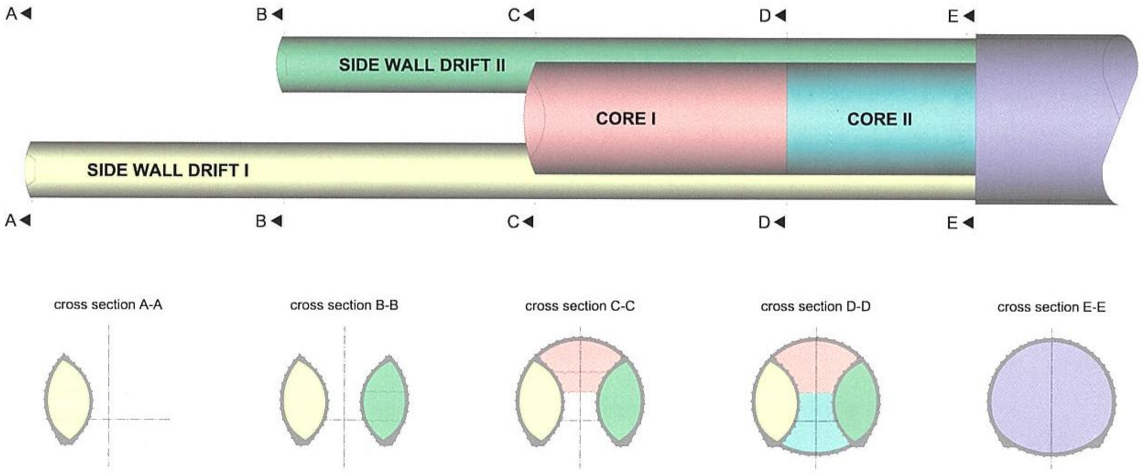


(b) Excavation sequence.

Fig. 8.3: Top heading-bench drive. Typical excation in soft ground conditions (ÖGG, 2010b).



(a) Excavation and support.



(b) Excavation squence.

Fig. 8.4: Side wall drift method (ÖGG, 2010b).

9 Literature

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