1 Introduction

1.1 General

Tunnelling is one of the most interesting, but also the most difficult engineering disciplines. It unites theory and practice into its own construction art. For the weighting of the many influential factors, practice is sometimes more important, and at other times theory, according to ones own state of knowledge. Tunnel engineering is normally performed by civil engineers. Everyone, however, should be aware that knowledge about structural analysis and concrete engineering alone is not sufficient. Geology, geomechanics, mechanical engineering and particularly construction process technology are equally important.

1.2 Historical development

Tunnels and caverns already existed in nature before mankind started to create them artificially to meet vital interests.

Tunnel engineering in the 20th century could also make use of existing specialised knowledge from mining. One of the founding fathers was Georg Agricola, whose 1556 work De Re Metallica, Libri XII covered mining and metallurgy.

Drill and blast

The building of significant tunnels in the Alps had already led to a first heyday of tunnelling before 1900, which explains why the railway engineer Franz Ržiha, mining superintendent of the duchy of Braunschweig, considered tunnel engineering as a separate discipline from mining in his 1867 textbook of tunnelling. This heyday continued to the start of the 20th century, after which there were only a few spectacular tunnel projects (Table 1-1) until 1960. The building of the Mont Blanc Tunnel was the start of a new phase in Europe, which continued with the construction of the Tauern Autobahn Tunnels, the Arlberg Tunnel and the new Gotthard Tunnel. The construction of more than a hundred tunnels by the German Railways (Deutsche Bundesbahn, later: Deutsche Bahn AG) continued the development. A new phase opened with the Seikan Tunnel, the Channel Tunnel and the base tunnels through the Alps.

The extent of the enormous development in tunnelling enabled by currently available support materials and machinery is illustrated in Fig. 1-1 and Fig. 1-2 for conventional tunnelling. The introduction of shotcrete as a means of support introduced a new phase of development, which made much greater use of machinery. Only years later did mechanisation take off again, permitting simultaneous working at the face and removal of the excavated material. The development of tunnel boring machines was even more impressive, and this is dealt with in detail in Chapter 6.

Handbook of Tunnel Engineering. Volume I: Structures and Methods. First English Edition.
Bernhard Maidl, Markus Thewes, Ulrich Maidl.

Table 1-1 Historical overview of some notable tunnels

	Year	Length m	Excavated quantity m³	Notes
Tunnel, water supply to Jerusalem (Palestine)	700 BC	540	20,000	Broken out with hammer and chisel
Eupalinos Tunnel (Samos)	500 BC	1,052	3,409	Broken out with hammer and chisel
Malpas Tunnel, Languedoc Canal (France)	1679 to 1681	175	9,000	Tuff partially loosened with fire
Galerie de Tronquoi canal, St. Quentin (France)	1803	500	30,000	Squeezing rock, partial-face excavation
Mont Cenis rail tunnel West Alps (France, Italy)	1857 to 1870	12,200	700,000	Drill and blast
St. Gotthard rail tunnel, central Alps (Switzerland)	1872 to 1878	14,990	1,100,000	Impact machine, drill and blast
Mont Blanc road tunnel, west Alps (France, Italy)	1959 to 1964	11,600	930,000	Drill and blast
Niagara Falls power station (Canada)	1950 to 1958		3,350,000	Drill and blast
Grande-Dixance power station group tunnel system (Switzerland)	1955 to 1964	150,000	1,500,000	Drill and blast
Gotthard road tunnel	1969 to 1980	16,322	1,300,000	Drill and blast
Arlberg Tunnel (Austria)	1974 to 1978	13,972	1,450,000	Drill and blast
Seikan Tunnel (Japan) Pilot tunnel	1964 to 1984	22,292	404,000	Initially TBM, then blast
Landrücken Tunnel for the new railway line Würzburg – Hannover	1983 to 1986	10,710	1,400,000	shotcrete lining, drill and blast
Channel Tunnel	1986 to 1993	50,450	10,028,749	Shield machine Ø = 8.72 m
Elbe Tunnel 4th bore	1997 to 2002	2,561	400,000	Shield machine Ø = 14.20 m
New railway line Cologne – Frankfurt Schulwald Tunnel	1997 to 2001	4,500	50,000	shotcrete lining
Rennsteig Tunnel A77	1998 to 2003	7,900	150,000	shotcrete lining
Lötschberg Tunnel SBB	1999 to approx. 2007	34,600	8,900,000	TBM, shotcrete lining
Gotthard Base Tunnel SBB	1999 to approx. 2011	57,000	13,300,000	TBM, shotcrete lining
Madrid M-30	2004 to 2006	8,344	1,506,092	Shield machine Ø = 15.16 m

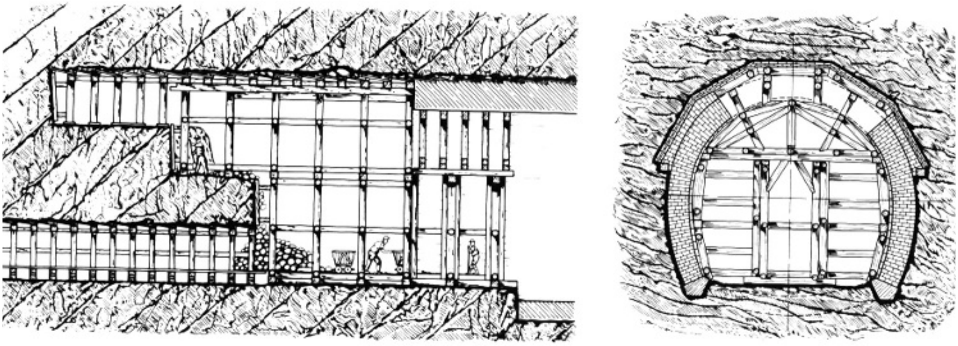

Figure 1-1 Construction of the Semmering Tunnel in 1848 using the old Austrian method [302]

Table 1-2 The data for the various Gotthard Tunnels

Project	Dates	Length km	Cross-section m²	Advance rate m/d	Cost, million sFr	Number of workers	Serious injuries	Accidental deaths
Rail tunnel	1872/81	14.9	45	3.5 to 4[a]	55.5	2500 to 4000	260 av. 8%	177 av. 5.4%
Road tunnel	1969/80	16.3	69 to 83 82 to 96	6[b]	560	up to 700	25 av. 3.5%	12 av. 1.7%
Base tunnel	1999/ 2011	57.0	41 standard, 250 MFS	approx. 1 to 20	About 10,000	Up to 1800	still being built	still being built

[a] In 2 x 12-h shifts and 7-day week. [b] In 2 x 10-h shifts (peak operation 3 x 8 h) and 5-day week.

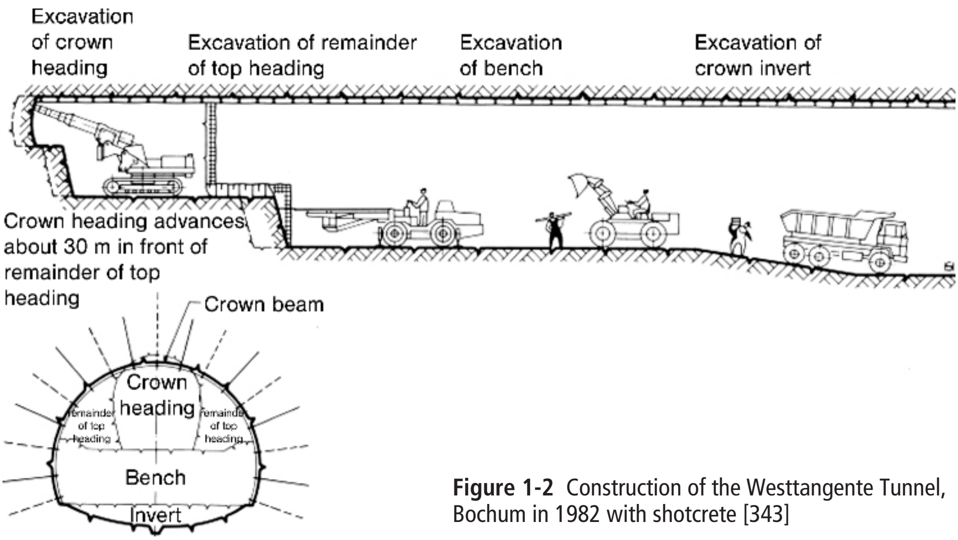

Figure 1-2 Construction of the Westtangente Tunnel, Bochum in 1982 with shotcrete [343]

Comparison of the data from the various Gotthard Tunnels in Table 1-2 shows that extremely short construction times were already possible many years ago, but the number of accidents has been greatly reduced by the modernisation of tunnelling technology.

Large underground structures have also been built for hydropower stations outside Europe, for example at Tarbela in Pakistan and Cabora Bassa in Mozambique. Many projects are still urgently needed, even if these have not yet been implemented due to financing problems. Underground and urban rapid transit lines, but also road tunnels will have to be extended to solve environmental and traffic problems in the cities. New developments in tunnel boring machines and in microtunnelling will assist the requirement in cities for environmentally friendly construction of extensive transport works, water supply and drainage, district heating, post and other utilities.

In German coal mining, development headings and drifts have amounted to annual totals of more about 100 km in rock and 400 km of coal roads in the past. As coal mining in Germany is discontinued, this will no longer be needed, although mining will maintain its significance outside Germany.

Tunnel boring machines

The development history of the first tunnel boring machine (TBM) has featured many tests that failed due to various problems, with the exception of the successful work of the Beaumont Machines in the Channel Tunnel. Sometimes the limitations of the available materials had not been considered, or else the ground to be driven through was simply not suitable for a TBM. Early applications proved successful where the ground offered ideal conditions for a TBM drive.

As early as 1851, the American Charles Wilson developed and built a tunnel boring machine, although he didn't patent it until 1856. This machine already showed all the features of a modern TBM and can thus be described as the first tunnel boring machine; see also Chapter 3.4.

Shield machines

Tunnel builders learnt long ago to support unstable rock or loose soil with timbering followed by a masonry lining. This was also successful in rock with seepage or joint water, but working below the water table in permeable soil or particularly under open water remained impossible well into the 19th century. The situation changed in 1806, as the ingenious engineer Sir Marc Isambard Brunel in London discovered the principle of the shield machine and later obtained a patent. The purpose of the invention was the building of a link across the Neva in St. Petersburg that could remain open in winter. As this project was not built, the machine was only developed on paper for the patent. Brunel was only able to try out his ideas in practice on the Thames Tunnel in London (see Chapter 3.4 "The Classic Shield Machines").

1.3 Terms and descriptions

In order to describe and understand underground structures, knowledge of the most important specialist terms and descriptions is essential. As there is not always a generally accepted term from the variety of terms derived from mining, preference has been given to those that have become most widely used and most precisely describe the subject (Table 1-3).

Table 1-3 Categories of underground structures [50, 51]

Structure	Examples	Purposes
Tunnels	Rail tunnels, Underground rail tunnels, road tunnels, canal tunnels	to provide transport routes
Small tunnels	*Main structures* Unpressurised tunnels, pressure tunnels, siphons Access tunnels Ventilation tunnels *Auxiliary structures* Grouting tunnels Pilot tunnels Viewing tunnels Adits	 transport of drainage water, drinking water and service water all-year access to caverns with avalanche protection supply of fresh air to underground cavities access for grouting works investigation of geological conditions surveying of underground structures to provide an additional starting point
Shafts	*Main structures* Inclined and vertical shafts *Auxiliary structures* Mucking shaft Surveying shaft	 transport of drinking water and drainage pressure relief (surge) in hydropower stations supply of fresh air to underground cavities transport of personnel and material transport of excavated material surveying
Pipelines	Sewers and drains Water supply pipes District heating pipes Gas supply pipes Oil pipelines Cable ducts	transport of goods, energy or news
Caverns	Industrial caverns Storage caverns Protection caverns	to house power station turbines or assembly halls storage of goods provision of underground shelters for the population in case of air raids or military bunkers
Chambers	Storage chambers Explosive chambers	storage of goods storage of explosives during the construction of a tunnel

Underground structures can be categorised according to the purpose of the completed structure:

Tunnels are extended, flat or only slightly sloping underground cavities with excavated cross-sections of over 20 m^2. They are mostly intended for road or rail transport. Each tunnel has two openings to the surface.

Adits, drifts or galleries are extended underground cavities, horizontal or sloping at less than 25° to the horizontal, with small diameters. They house pipes or cables or provide access and serve as auxiliary structures during the construction phase or for permanent use. They often only have one opening to the surface.

Shafts are extended, underground, vertical or inclined (more than 25° to the horizontal) cavities to overcome level differences. They serve similar purpose to adits, drifts or galleries.

Underground **pipes** mostly have inaccessible cross-sections. They serve to transport liquids, heat or gases and to house cables (ducts).

Caverns are underground cavities with large cross-sections and relatively short lengths. They serve for the storage of solid, liquid or gaseous goods, to house machinery and vehicles, underground generation plant, assembly halls and military facilities. They are normally connected to the surface through tunnels, adits or shafts.

Chambers are small compact underground cavities. They serve for the storage of goods during construction work or permanently.

The terms for individual parts of a structure that are normally used in underground construction are shown in Figs. 1.3 and 1.4 in cross-section and Fig. 1-5 along the tunnel. The basic terms are explained in more detail below.

Tunnel driving denotes the entirety of excavation works to advance underground cavities.

Temporary support denotes the temporary support of the excavated cavity until the complete installation of the permanent lining. The temporary support can also provide part of the structural function of the permanent lining if it is integrated. The temporary support may also be described as:

– excavation support.
– temporary lining.
– outer lining.
– primary lining.
– shoring, timbering or lagging.

The **lining** provides the structural support of the cavity and waterproofing measures. It may also be described as the secondary lining, inner lining or permanent support.

Installations are structures and fittings required for the operation of the completed tunnel. This can include dividing slabs and partitions, wall linings, cable ducts and channels and technical equipment.

The **construction process** denotes the entirety of the technical and organisational measures used for the implementation of the tunnel drive, the temporary support and the lining. The construction process is characterised by the *construction method* and the *operational method*.

The **construction method** is the sequence of construction activities in the excavated cross-section and refers to the division of the excavation cross-section into partial sections for excavation, temporary support and lining (see Fig. 1-1 to 1.3).

The **operational method** is the sequence of construction activities along the tunnel and refers to excavation and support activities, but also to supply and disposal activities along the entire length of the tunnel (see also Fig. 1-1 and Fig. 1-2).

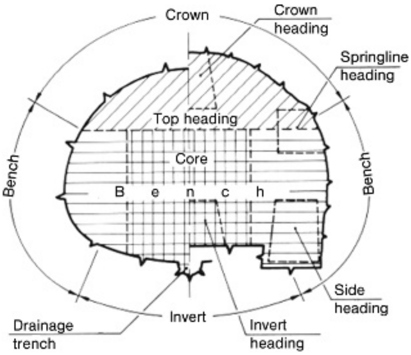

Figure 1-3 Description of the parts of a cross-section

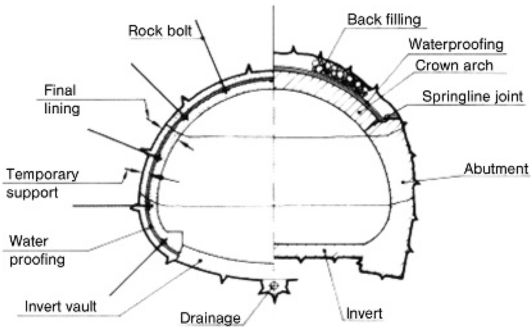

Figure 1-4 Description of the parts of the support system

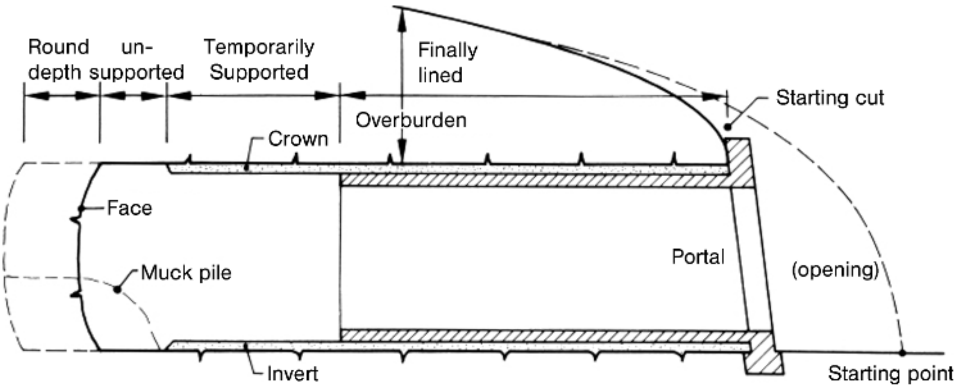

Figure 1-5 Description of the parts of a longitudinal section

Tunnel portals are the structure provided at the ends of a tunnel to support against slope sliding, lateral earth pressure and falling rock (Fig. 1-5). Tunnel portals should also fit the tunnel into the landscape.

Waterproofing is the description of measures to protect the structure against water ingress from outside and also to prevent the escape of liquids to the outside.

Isolation denotes measures to protect the structure, adjacent buildings and cables against unwanted electrical effects.