Tunnels in Civil Engineering

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Chapter 1

Tunnel

Underground tunnel for heatpipes between Rigshospitalet and Amagerværket in Denmark.

Underground railway tunnel on the Taipei Metro in Taiwan.

A **tunnel** is an underground passageway, completely enclosed except for openings for egress, commonly at each end.

A tunnel may be for foot or vehicular road traffic, for rail traffic, or for a canal. Some tunnels are aqueducts to supply water for consumption or for hydroelectric stations or are sewers. Other uses include routing power or telecommunication cables, some are to permit wildlife such as European badgers to cross highways. Secret tunnels have given entrance to or escape from an area, such as the Cu Chi Tunnels or the smuggling tunnels in the Gaza Strip which connect it to Egypt. Some tunnels are not for transport at all but rather, are fortifications, for example Mittelwerk and Cheyenne Mountain.

In the United Kingdom, a pedestrian tunnel or other underpass beneath a road is called a underpass subway. In the United States that term now means an underground rapid transit system.

The central part of a rapid transit network is usually built in tunnels. Rail station platforms may be connected by pedestrian tunnels or by foot bridges.

Usage limitations

A tunnel is relatively long and narrow; in general the length is more (usually much more) than twice the diameter. Some hold a tunnel to be at least 0.160 kilometres (0.10 mi) long and call shorter passageways by such terms as an "underpass" or a "chute". For example, the underpass beneath Yahata Station in Kitakyushu, Japan is 0.130 km long (0.081 mi) and so might not be considered a tunnel.

Geotechnical investigation

A tunnel project must start with a comprehensive investigation of ground conditions by collecting samples from boreholes and by other geophysical techniques. An informed choice can then be made of machinery and methods for excavation and ground support, which will reduce the risk of encountering unforeseen ground conditions. In planning the route the horizontal and vertical alignments will make use of the best ground and water conditions.

In some cases conventional desk and site studies yield insufficient information to assess such factors as the blocky nature of rocks, the exact location of fault zones, or the stand-up times of softer ground. This may be a particular concern in large diameter tunnels. To give more information a pilot tunnel, or drift, may be driven ahead of the main drive. This smaller diameter tunnel will be easier to support should unexpected conditions be met, and will be incorporated in the final tunnel. Alternatively, horizontal boreholes may sometimes be drilled ahead of the advancing tunnel face.

Construction

Cut-and-cover constructions of the Paris Métro in France

The construction of a Tunnel at Monza, Italy

Tunnels are dug in types of materials varying from soft clay to hard rock. The method of tunnel construction depends on such factors as the ground conditions, the ground water conditions, the length and diameter of the tunnel drive, the depth of the tunnel, the logistics of supporting the tunnel excavation, the final use and shape of the tunnel and appropriate risk management.

There are three basic types of tunnel construction in common use:

- Cut and cover tunnels, constructed in a shallow trench and then covered over.
- Bored tunnels, constructed in situ, without removing the ground above. They are usually of circular or horseshoe cross-section.
- Immersed tube tunnels, sunk into a body of water and sit on, or are buried just under, its bed.

Cut-and-cover

Cut-and-cover is a simple method of construction for shallow tunnels where a trench is excavated and roofed over with an overhead support system strong enough to carry the load of what is to be built above the tunnel. Two basic forms of cut-and-cover tunnelling are available:

- *Bottom-up method*: A trench is excavated, with ground support as necessary, and the tunnel is constructed in it. The tunnel may be of in situ concrete, precast concrete, precast arches,or corrugated steel arches; in early days brickwork was used. The trench is then carefully back-filled and the surface is reinstated.
- *Top-down method*: Here side support walls and capping beams are constructed from ground level by such methods as slurry walling, or contiguous bored piling. Then a shallow excavation allows making the tunnel roof of precast beams or in situ concrete. The surface is then reinstated except for access openings. This allows early reinstatement of roadways, services and other surface features. Excavation then takes place under the permanent tunnel roof, and the base slab is constructed.

Shallow tunnels are often of the cut-and-cover type (if under water, of the immersed-tube type), while deep tunnels are excavated, often using a tunnelling shield. For intermediate levels, both methods are possible.

Large cut-and-cover boxes are often used for underground metro stations, such as Canary Wharf tube station in London. This construction form generally has two levels, which allows economical arrangements for ticket hall, station platforms, passenger access and emergency egress, ventilation and smoke control, staff rooms, and equipment rooms. The interior of Canary Wharf station has been likened to an underground cathedral, owing to the sheer size of the excavation. This contrasts with most traditional stations on London Underground, where bored tunnels were used for stations and passenger access.

Clay-kicking

Clay-kicking is a specialised method developed in the United Kingdom, of manually digging tunnels in strong clay-based soil structures. Unlike previous manual methods of using mattocks which relied on the soil structure to be hard, clay-kicking was relatively silent and hence did not harm soft clay based structures.

The clay-kicker lies on a plank at a 45degree angle away from the working face, and inserts a tool with a cup-like rounded end with his feet. Turning the tool with his hands, he extracts a section of soil, which is then placed on the waste extract.

Regularly used in Victorian civil engineering, the methods found favour in the renewal of the United Kingdom's then ancient sewerage systems, by not having to remove all property or infrastructure to create an effective small tunnel system. During the First World War, the system was successfully deployed by the Royal Engineer tunnelling companies to deploy large military mines beneath enemy German Empire lines. The method was virtually silent not susceptible to listening methods of detection.

Boring machines

A tunnel boring machine that was used at Yucca Mountain, Nevada, United States

Tunnel boring machines (TBMs) and associated back-up systems are used to highly automate the entire tunneling process, reducing tunneling costs.

Tunnel boring in certain predominantly urban applications, is viewed as quick and cost effective alternative to laying surface rails and roads. Expensive compulsory purchase of buildings and land with potentially lengthy planning inquiries is eliminated.

There are a variety of TBMs that can operate in a variety of conditions, from hard rock to soft water-bearing ground. Some types of TBMs, bentonite slurry and earth-pressure balance machines, have pressurised compartments at the front end, allowing them to be used in difficult conditions below the water table. This pressurizes the ground ahead of the TBM cutter head to balance the water pressure. The operators work in normal air pressure behind the pressurised compartment, but may occasionally have to enter that compartment to renew or repair the cutters. This requires special precautions, such as local ground treatment or halting the TBM at a position free from water. Despite these difficulties, TBMs are now preferred to the older method of tunneling in compressed air, with an air lock/decompression chamber some way back from the TBM, which required operators to work in high pressure and go through decompression procedures at the end of their shifts, much like divers.

In February 2010, Aker Wirth delivered a TBM to Switzerland, for the expansion of Linth Limmern Power Plant in Switzerland. The borehole has a diameter of 8.03 metres (26.3 ft). The TBM used for digging the 57-kilometre (35 mi) Gotthard Base Tunnel, in Switzerland, has a diameter of about 9 metres (30 ft). A larger TBM was built to bore the Green Heart Tunnel (Dutch: Tunnel Groene Hart) as part of the HSL-Zuid in the Netherlands, with a diameter of 14.87 metres (48.8 ft). This in turn was superseded by the Madrid M30 ringroad, Spain, and the Chong Ming tunnels in Shanghai, China. All of these machines were built at least partly by Herrenknecht.

Shafts

A shaft is sometimes necessary for a tunnel project. They are usually circular and go straight down until they reach the level at which the tunnel is going to be built. A shaft normally has concrete walls and is built just like it is going to be permanent. Once they are built the Tunnel Boring Machines are lowered to the bottom and excavation can start. Shafts are the main entrance in and out of the tunnel until the project is completed. Sometimes if a tunnel is going to be long there will be multiple shafts at various locations so that entrance into the tunnel is closer to the unexcavated area.

Other key factors

- Stand-up time is the amount of time a tunnel will support itself without any added structures. Knowing this time allows the engineers to determine how much can be excavated before support is needed. The longer the stand-up time is the faster the excavating will go. Generally certain configurations of rock and clay will have the greatest stand-up time, and sand and fine soils will have a much lower stand-up time.
- Groundwater control is very important in tunnel construction. If there is water leaking into the tunnel stand-up time will be greatly decreased. If there is water leaking into the shaft it will become unstable and will not be safe to work in. To stop this from happening there are a few common methods. One of the most effective is ground freezing. To do this pipes are inserted into the ground surrounding the shaft and are cooled until they freeze. This freezes the ground around each pipe until the whole shaft is surrounded frozen soil, keeping water out. The most common method is to install pipes into the ground and to simply pump the water out. This works for tunnels and shafts.
- Tunnel shape is very important in determining stand-up time. The force from gravity is straight down on a tunnel, so if the tunnel is wider than it is high it will have a harder time supporting itself decreasing its stand-up time. If a tunnel is higher than it is wide the stand up time will increase making the project easier. The hardest shape to support itself is a square or rectangular tunnel. The forces have a harder time being redirected around the tunnel making it extremely hard to support itself. This of course all depends what the material of the ground is.

Sprayed concrete techniques

The **New Austrian Tunneling Method** (NATM) was developed in the 1960s, and is the best known of a number of engineering solutions that use calculated and empirical real-time measurements to provide optimised safe support to the tunnel lining. The main idea of this method is to use the geological stress of the surrounding rock mass to stabilize the tunnel itself, by allowing a measured relaxation and stress reassignment into the surrounding rock to prevent full loads becoming imposed on the introduced support measures. Based on geotechnical measurements, an optimal cross section is computed. The excavation is immediately protected by a layer of sprayed concrete, commonly referred to as shotcrete, after excavation. Other support measures could include steel arches, rockbolts and mesh. Technological developments in sprayed concrete technology have resulted in steel and polypropylene fibres being added to the concrete mix to improve lining strength. This creates a natural load-bearing ring, which minimizes the rock's deformation.

Illowra Battery utility tunnel, Port Kembla. One of many bunkers south of Sydney.

By special monitoring the NATM method is very flexible, even at surprising changes of the geomechanical rock consistency during the tunneling work. The measured rock properties lead to appropriate tools for tunnel strengthening. In the last decades also soft ground excavations up to 10 kilometres (6.2 mi) became usual.

Pipe jacking

Pipe Jacking, also known as **pipejacking** or **pipe-jacking**, is a method of tunnel construction where hydraulic jacks are used to push specially made pipes through the ground behind a tunnel boring machine or shield. This technique is commonly used to create tunnels under existing structures, such as roads or railways. Tunnels constructed by pipe jacking are normally small diameter tunnels with a maximum size of around 2.4m.

Box jacking

Box jacking is similar to pipe jacking, but instead of jacking tubes, a box shaped tunnel is used. Jacked boxes can be a much larger span than a pipe jack with the span of some box jacks in excess of 20m. A cutting head is normally used at the front of the box being jacked and excavation is normally by excavator from within the box.

Underwater tunnels

There are also several approaches to underwater tunnels, the two most common being bored tunnels or immersed tubes. Submerged floating tunnels are another approach that has not been constructed.

Other

Other tunneling methods include:

- Drilling and blasting
- Slurry-shield machine
- Wall-cover construction method.

Costs and cost overruns of tunnels

Tunnels are costly and generally more costly than bridges. Large cost overruns are common in tunnel construction. Costs and cost overruns are documented in and

Choice of tunnels vs. bridges

For water crossings, a tunnel is generally more costly to construct than a bridge. Navigational considerations may limit the use of high bridges or drawbridge spans intersecting with shipping channels, necessitating a tunnel.

Bridges usually require a larger footprint on each shore than tunnels. There are actually more codes to follow with bridges than with tunnels. In areas with expensive real estate, such as Manhattan and urban Hong Kong, this is a strong factor in tunnels' favor. Boston's Big Dig project replaced elevated roadways with a tunnel system to increase traffic capacity, hide traffic, reclaim land, redecorate, and reunite the city with the waterfront.

The 1934 Queensway Road Tunnel under the River Mersey at Liverpool, was chosen over a massively high bridge for defence reasons. It was feared aircraft could destroy a bridge in times of war. Maintenance costs of a massive bridge to allow the world's largest ships navigate under was considered higher than a tunnel. Similar conclusions were met for the 1971 Kingsway Tunnel under the River Mersey.

The Queens–Midtown Tunnel in New York City serves as an example of a water-crossing tunnel built instead of a bridge.

Examples of water-crossing tunnels built instead of bridges include the Holland Tunnel, Queens-Midtown Tunnel and Lincoln Tunnel between New Jersey and Manhattan in New York City, and the Elizabeth River tunnels between Norfolk and Portsmouth, Virginia, the 1934 River Mersey road Queensway Tunnel and the Western Scheldt Tunnel, Zeeland, Netherlands.

Other reasons for choosing a tunnel instead of a bridge include avoiding difficulties with tides, weather and shipping during construction (as in the 51.5-kilometre or 32.0 mi Channel Tunnel), aesthetic reasons (preserving the above-ground view, landscape, and scenery), and also for weight capacity reasons (it may be more feasible to build a tunnel than a sufficiently strong bridge).

Some water crossings are a mixture of bridges and tunnels, such as the Denmark to Sweden link and the Chesapeake Bay Bridge-Tunnel in the eastern United States.

There are particular hazards with tunnels, especially from vehicle fires when combustion gases can asphyxiate users, as happened at the Gotthard Road Tunnel in Switzerland in

2001. One of the worst railway disasters ever, the Balvano train disaster, was caused by a train stalling in the Armi tunnel in Italy in 1944, killing 426 passengers.

Variant tunnel types

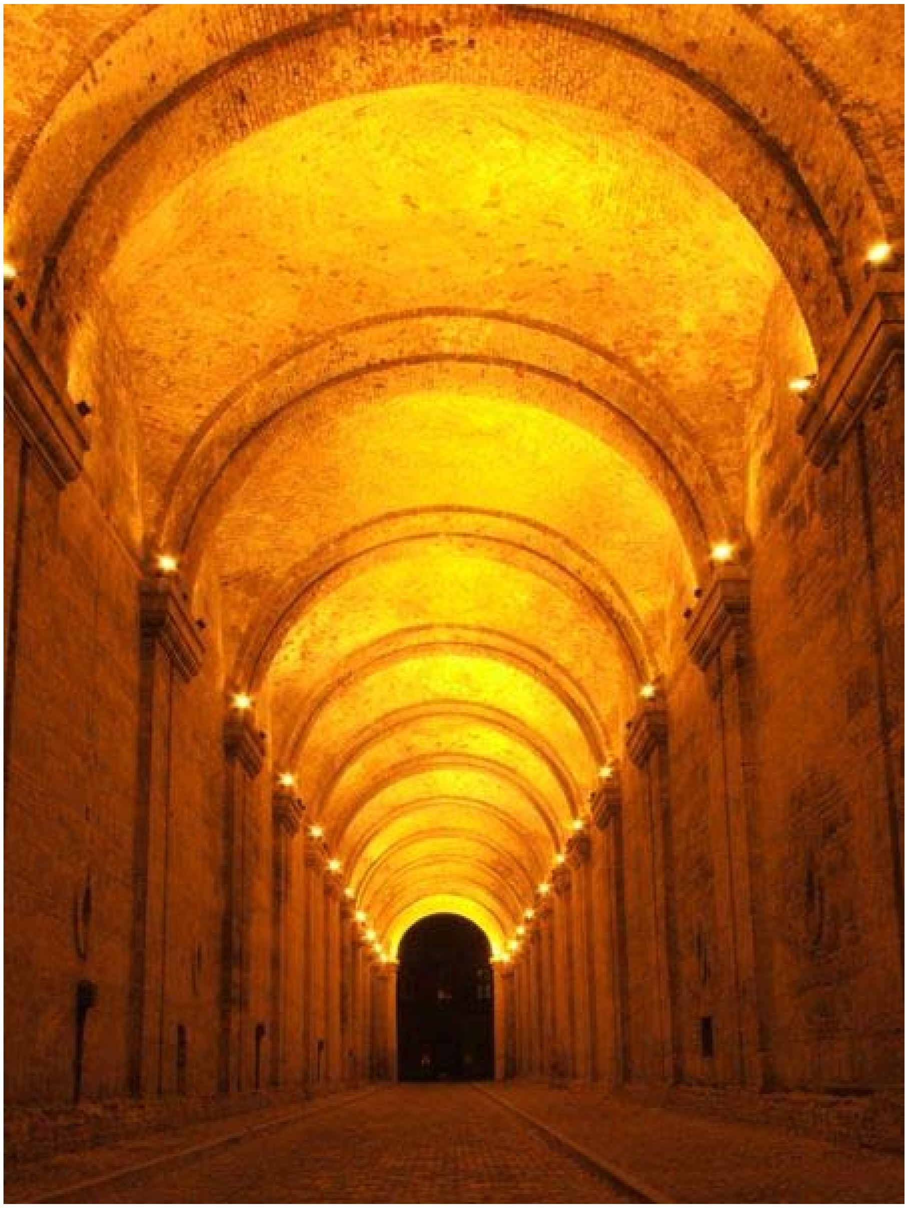
Double-deck tunnel

Some tunnels are double-deck, for example the two major segments of the San Francisco – Oakland Bay Bridge (completed in 1936) are linked by a double-deck tunnel, once the largest diameter tunnel in the world. At construction this was a combination bidirectional rail and truck pathway on the lower deck with automobiles above, now converted to one-way road vehicle traffic on each deck.

A recent double-decker tunnel with both decks for motor vehicles is the Fuxing Road Tunnel in Shanghai, China. Cars travel on the two-lane upper deck and heavier vehicles on the single-lane lower.

Multipurpose tunnel are tunnels that have more than one purpose. The SMART Tunnel in Malaysia is the first multipurpose tunnel in the world, as it is used both to control traffic and flood in Kuala Lumpur.

Artificial tunnels



The 19th century Dark Gate in Esztergom, Hungary.

Overbridges can sometimes be built by covering a road or river or railway with brick or still arches, and then levelling the surface with earth. In railway parlance, a surface-level track which has been built or covered over is normally called a covered way.

Snow sheds are a kind of artificial tunnel built to protect a railway from avalanches of snow. Similarly the Stanwell Park, New South Wales **steel tunnel**, on the South Coast railway line, protects the line from rockfalls.

Common utility ducts are man-made tunnels created to carry two or more utility lines underground. Through co-location of different utilities in one tunnel, organizations are able to reduce the costs of building and maintaining utilities.

Hazards

Owing to the enclosed space of a tunnel, fires can have very serious effects on users. The main dangers are gas and smoke production, with low concentrations of carbon monoxide being highly toxic. Fires killed 11 people in the Gotthard tunnel fire of 2001 for example, all of the victims succumbing to smoke and gas inhalation. Over 400 passengers died in the Balvano train disaster in Italy in 1944, when the locomotive halted in a long tunnel. Carbon monoxide poisoning was the main cause of the horrifying death rate.

Examples of tunnels

In history

A short section remains of the 1836 Edge Hill to Lime Street tunnel in Liverpool. This is the oldest used rail tunnel in the world. A tilting train passes through the tunnel.

Lehigh Tunnel, Pennsylvania

- The World's oldest underwater tunnel is rumored to be the *Terelek kaya tüneli* under Kızıl River, a little south of the towns of Boyabat and Duragan in Turkey. Estimated to have been built more than 2000 years ago (possibly 5000), it is assumed to have had a defence purpose.
- The qanat or kareez of Persia is a water management system used to provide a reliable supply of water to human settlements or for irrigation in hot, arid and semi-arid climates. The oldest and largest known qanat is in the Iranian city of Gonabad, which after 2700 years, still provides drinking and agricultural water to nearly 40,000 people. Its main well depth is more than 360 m (1,180 ft), and its length is 45 km (28 mi).
- The Eupalinian aqueduct on the island of Samos (North Aegean, Greece). Built in 520 BC by the ancient Greek engineer Eupalinos of Megara. Eupalinos organised the work so that the tunnel was begun from both sides of mount Kastro. The two teams advanced simultaneously and met in the middle with excellent accuracy, something that was extremely difficult in that time. The aqueduct was of utmost defensive importance, since it ran underground, and it was not easily found by an enemy who could otherwise cut off the water supply to Pythagoreion, the ancient capital of Samos. The tunnel's existence was recorded by Herodotus (as was the mole and harbour, and the third wonder of the island, the great temple to Hera,

thought by many to be the largest in the Greek world). The precise location of the tunnel was only re-established in the 19th century by German archaeologists. The tunnel proper is 1,030 m long (3,380 ft) and visitors can still enter it Eupalinos tunnel.

- The Via Flaminia, an important Roman road, penetrated the Furlo pass in the Apennines through a tunnel which emperor Vespasian had ordered built in 76-77. A modern road, the SS 3 Flaminia, still uses this tunnel, which had a precursor dating back to the 3rd century BC; remnants of this earlier tunnel (one of the first road tunnels) are also still visible.
- Sapperton Canal Tunnel on the Thames and Severn Canal in England, dug through hills, which opened in 1789, was 3.5 km (2.2 mi) long and allowed boat transport of coal and other goods. Above it runs the Sapperton Long Tunnel which carries the "Golden Valley" railway line between Swindon and Gloucester.
- The 1796 Stoddart Tunnel in Chapel-en-le-Frith in Derbyshire is reputed to be the oldest rail tunnel in the world. Rail wagons were horse-drawn.
- The tunnel was created for the first true steam locomotive, from Penydarren to Abercynon. The Penydarren locomotive was built by Richard Trevithick. The locomotive made the historic journey from Penydarren to Abercynon in 1804. Part of this tunnel can still be seen at Pentrebach, Merthyr Tydfil, Wales. This is arguably the oldest railway tunnel in the world, for self-propelled steam engines on rails.
- The Montgomery Bell Tunnel in Tennessee, a 88 m (289 ft), high water diversion tunnel, 4.50-×-2.45 m high (15-×-8.0 ft), to power a water wheel, was built by slave labour in 1819, being the first full-scale tunnel in North America.
- Crown Street Station, Liverpool, 1829. Built by George Stephenson, a single track tunnel 291 yd long (266 m) was bored from Edge Hill to Crown Street to serve the world's first passenger railway station. The station was abandoned in 1836 being too far from Liverpool city centre, with the area converted for freight use. Closed down in 1972, the tunnel is disused. However it is the oldest rail tunnel running under streets in the world.
- The 1.26 mile (2.03 km) 1829 Wapping Tunnel in Liverpool, England, was the first rail tunnel bored under a metropolis. Currently disused since 1972. Having two tracks, the tunnel runs from Edge Hill in the east of the city to the south end Liverpool docks being used only for freight. The tunnel is still in excellent condition and is being considered for reuse by Merseyrail rapid transit rail system, with maybe an underground station cut into the tunnel. The river portal is opposite the new Liverpool Arena being ideal for a serving station. If reused it will be the oldest used underground rail tunnel in the world and oldest part of any underground metro system.
- 1836, Lime St Station tunnel, Liverpool. A two track rail tunnel, 1.13 miles (1,811 m) long was bored under a metropolis from Edge Hill in the east of the city to Lime Street. In the 1880s the tunnel was converted to a deep cutting four tracks wide. The only occurrence of a tunnel being removed. A very short section of the original tunnel still exists at Edge Hill station making this the oldest rail tunnel in the world still in use, and the oldest in use under a street, albeit only one street and one building.

- Box Tunnel in England, which opened in 1841, was the longest railway tunnel in the world at the time of construction. It was dug and has a length of 2.9 km (1.8 mi).
- The 0.75 mile long 1842 Prince of Wales Tunnel, in Shildon near Darlington, England, is the oldest sizable tunnel in the world still in use under a settlement.
- The Thames Tunnel, built by Marc Isambard Brunel and his son Isambard Kingdom Brunel and opened in 1843, was the first underwater tunnel and the first to use a tunnelling shield. Originally used as a foot-tunnel, it was a part of the East London Line of the London Underground until 2007, being the oldest section of the system. From 2010 the tunnel becomes a part of the London Overground system.
- The 2.07 miles (3.34 km) Victoria Tunnel in Liverpool, opened in 1848, was bored under a metropolis. Initially used only for rail freight and later freight and passengers serving the Liverpool ship liner terminal, the tunnel runs from Edge Hill in the east of the city to the north end Liverpool docks. Used until 1972 it is still in excellent condition, being considered for reuse by the Merseyrail rapid transit rail system. Stations being cut into the tunnel are being considered. Also, reuse by a monorail system from the proposed Liverpool Waters redevelopment of Liverpool's Central Docks has been proposed.
- The oldest underground sections of the London Underground were built using the cut-and-cover method in the 1860s. The Metropolitan, Hammersmith & City, Circle and District lines were the first to prove the success of a metro or subway system. Dating from 1863, Baker Street station is the oldest underground station in the world.
- The 1882 Col de Tende Road Tunnel, at 3182 metres long, was one of the first long road tunnels under a pass, running between France and Italy.
- The Mersey Railway tunnel opened in 1886 running from Liverpool to Birkenhead under the River Mersey. The Mersey Railway was the world's first deep-level underground railway. By 1892 the extensions on land from Birkenhead Park station to Liverpool Central Low level station gave a tunnel 3.12 miles (5029 m) in length. The under river section is 0.75 miles in length, being the longest underwater tunnel in world in January 1886.
- The rail Severn Tunnel was opened in late 1886, at 4 miles 624 yd (7,008 m) long, although only 2¼ miles (3.62 km) of the tunnel is actually under the river. The tunnel replaced the Mersey Railway tunnel's longest under water record, which it held for less than a year.
- James Greathead, in constructing the City & South London Railway tunnel beneath the Thames, opened in 1890, brought together three key elements of tunnel construction under water: 1) shield method of excavation; 2) permanent cast iron tunnel lining; 3) construction in a compressed air environment to inhibit water flowing through soft ground material into the tunnel heading.
- St. Clair Tunnel, also opened later in 1890, linked the elements of the Greathead tunnels on a larger scale.
- The 1927 Holland Tunnel was the first underwater tunnel designed for automobiles. This fact required a novel ventilation system.

Longest

- The Delaware Aqueduct in New York USA is the longest tunnel, of any type, in the world at 137 km (85 mi). It is drilled through solid rock.
- The Gotthard Base Tunnel is the longest rail tunnel in the world at 57 km (35 mi). It will be totally completed in 2017.
- The Seikan Tunnel in Japan was the longest rail tunnel in the world at 53.9 km (33.5 mi), of which 23.3 km (14.5 mi) is under the sea.
- The Channel Tunnel between France and the United Kingdom under the English Channel is the second-longest, with a total length of 50 km (31 mi), of which 39 km (24 mi) is under the sea.
- The Lötschberg Base Tunnel opened in June 2007 in Switzerland was the longest land rail tunnel, with a total of 34.5 km (21.4 mi).
- The Lærdal Tunnel in Norway from Lærdal to Aurland is the world's longest road tunnel, intended for cars and similar vehicles, at 24.5 km (15.2 mi).
- The Zhongnanshan Tunnel in People's Republic of China opened in January 2007 is the world's second longest highway tunnel and the longest road tunnel in Asia, at 18 km (11 mi).
- The longest canal tunnel is the Rove Tunnel in France, over 7.12 km (4.42 mi) long.

Notable

- The Lincoln Tunnel between New Jersey and New York is one of the busiest vehicular tunnels in the United States, at 120,000 vehicles/day.
- The Central Artery Tunnel in Boston carries approximately 200,000 vehicles/day.
- The Fredhälls Tunnel in Stockholm, Sweden, and the New Elbe Tunnel in Hamburg, Germany, both with around 150,000 vehicles a day, two of the most trafficked tunnels in the world.
- Gerrards Cross tunnel in Britain is notable in that it is being built over a railway cutting that was dug in the early part of the 20th Century. Thus, arguably, making it the tunnel longest in construction by the cut and cover method. When complete a branch of the Tesco supermarket chain will occupy the space above the railway tunnel.
- Williamson's tunnels in Liverpool, built by a wealthy eccentric are probably the largest underground folly in the world.
- New York City Water Tunnel No. 3, started in 1970, has an expected completion date of 2020.
- The Chicago Deep Tunnel Project is a network of 175 km (109 mi) of tunnels designed to reduce flooding in the Chicago area. Started in the mid 1970s, the project is due to be completed in 2019.
- Moffat Tunnel in Colorado straddles the Continental Divide. The tunnel is 6.2 mi (10.0 km) long and at 9,239 ft (2,816 m) above sea level is the highest railroad tunnel in the United States.
- The Fenghuoshan tunnel on Qinghai-Tibet railway is the world's highest railway tunnel, about 4,905 m (16,093 ft) above sea level.

- The La Linea Tunnel in Colombia, will be (2013) the longest, 8.58 km (5.33 mi), mountain tunnel in South America. It crosses beneath a mountain at 2,500 m (8,202.1 ft) above sea level with six lanes and it has a parallel emergency tunnel. The tunnel is subject to serious groundwater pressure. The tunnel, which is currently under construction, will link Bogotá and its urban area with the coffee-growing region and with the main port on the Colombian Pacific coast.
- The Honningsvåg Tunnel (4.443 km (2.76 mi) long) on European route E69 in Norway is the world's northernmost road tunnel, except for mines (which exist on Svalbard).
- The Eiksund Tunnel on national road Rv 653 in Norway is the world's deepest subsea road tunnel (7,776 m long, with deepest point at -287 metres below the sea level, opened in feb. 2008)

Other uses

Excavation techniques, as well as the construction of underground bunkers and other habitable areas, are often associated with military use during armed conflict, or civilian responses to threat of attack. The use of tunnels for mining is called drift mining. One of the strangest uses of a tunnel was for the storage of chemical weapons .

Natural tunnels

- Lava tubes are partially empty, cave-like conduits underground, formed during volcanic eruptions by flowing and cooling lava.
- Natural Tunnel State Park (Virginia, USA) features an 850-foot (259 m) natural tunnel, really a limestone cave, that has been used as a railroad tunnel since 1890.
- Punarjani Guha Kerala, India. Hindus believe that crawling through the tunnel (which they believe was created by a Hindu god) from one end to the other will wash away all of one's sins and thus attain rebirth, although only men are permitted to crawl through the cave.
- Small "snow tunnels" are created by voles, chipmunks and other rodents for protection and access to food sources.

Temporary way

During construction of a tunnel it is often convenient to install a temporary railway particularly to remove spoil. This temporary railway is often narrow gauge so that it can be double track, which facilitates the operation of empty and loaded trains at the same time. The temporary way is replaced by the permanent way at completion, thus explaining the term Perway.

Enlargement

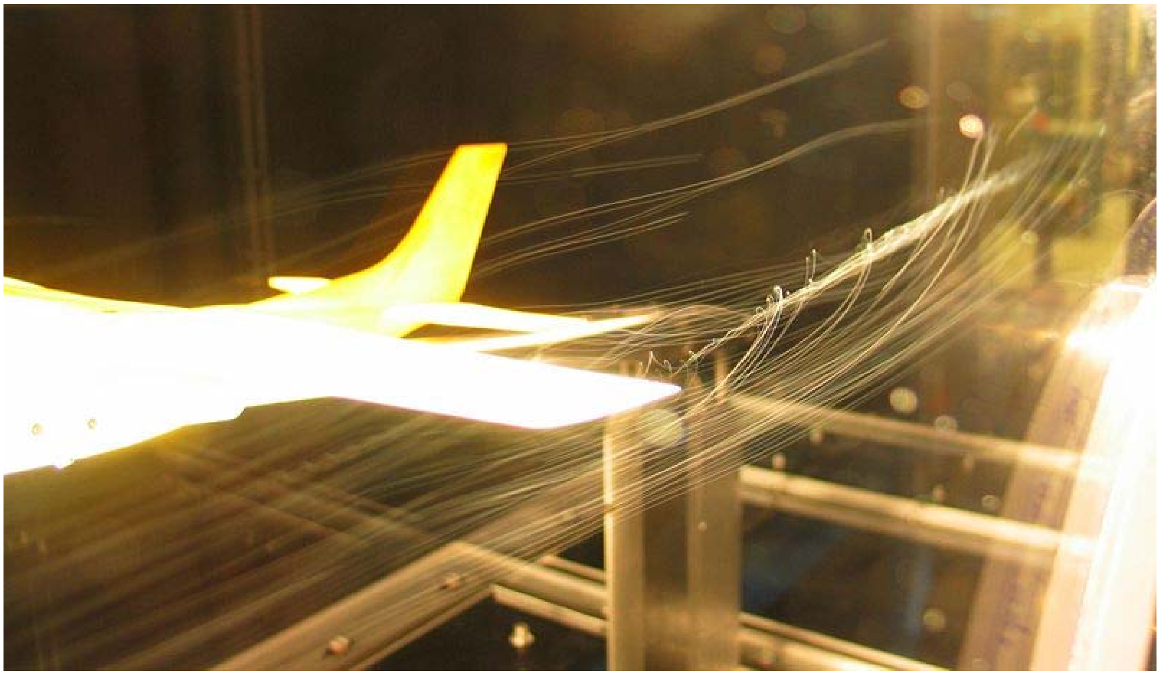
The vehicles using a tunnel can outgrow it, requiring replacement or enlargement. The original single line Gib Tunnel near Mittagong was replaced with a double line tunnel, with the original tunnel used for growing mushrooms. The Rhyndaston Tunnel was enlarged using a borrowed Tunnel Boring Machine so as to be able to take ISO containers.

The 1836 Lime Street two track 1 mile tunnel from Edge Hill to Lime Street in Liverpool was totally removed, apart from a short 50 metre section at Edge Hill. Four tracks were required. The tunnel was converted into a very deep 4 track open cutting. However, short larger 4 track tunnels were left in some parts of the run. Train services were not interrupted as the work progressed. Photos of the work in progress: There are other occurrences of tunnels being replaced by open cuts, for example, the Auburn Tunnel.

Chapter 2

Wind Tunnel

NASA wind tunnel with the model of a plane.



A model Cessna with helium-filled bubbles showing streamlines of the wingtip vortices.

A **wind tunnel** is a research tool used in aerodynamic research. It is used to study the effects of air moving past solid objects.

Theory of operation

Wind tunnels were first proposed as a means of studying vehicles (primarily airplanes) in free flight. The wind tunnel was envisioned as a means of reversing the usual paradigm: instead of the air's standing still and the aircraft moving at speed through it, the same effect would be obtained if the aircraft stood still and the air moved at speed past it. In that way a stationary observer could study the aircraft in action, and could measure the aerodynamic forces being imposed on the aircraft.

Later, wind tunnel study came into its own: the effects of wind on manmade structures or objects needed to be studied, when buildings became tall enough to present large surfaces to the wind, and the resulting forces had to be resisted by the building's internal structure. Determining such forces was required before building codes could specify the required strength of such buildings.

Still later, wind-tunnel testing was applied to automobiles, not so much to determine aerodynamic forces *per se* but more to determine ways to reduce the power required to move the vehicle on roadways at a given speed. In these studies, the interaction between the road and the vehicle plays a significant role, and this interaction must be taken into consideration when interpreting the test results. In an actual situation the roadway is moving relative to the vehicle but the air is stationary relative to the roadway, but in the wind tunnel the air is moving relative to the roadway, while the roadway is stationary relative to the test vehicle. Some automotive-test wind tunnels have incorporated moving belts under the test vehicle in an effort to approximate the actual condition.

Measurement of aerodynamic forces

Ways that air velocity and pressures are measured in wind tunnels:

- air velocity through the test section is determined by Bernoulli's principle. Measurement of the dynamic pressure, the static pressure, and (for compressible flow only) the temperature rise in the airflow
- direction of airflow around a model can be determined by tufts of yarn attached to the aerodynamic surfaces
- direction of airflow approaching an aerodynamic surface can be visualized by mounting threads in the airflow ahead of and aft of the test model
- dye, smoke, or bubbles of liquid can be introduced into the airflow upstream of the test model, and their path around the model can be photographed
- pressures on the test model are usually measured with beam balances, connected to the test model with beams or strings or cables
- pressure distributions across the test model have historically been measured by drilling many small holes along the airflow path, and using multi-tube manometers to measure the pressure at each hole
- pressure distributions can more conveniently be measured by the use of pressure-sensitive paint, in which higher local pressure is indicated by lowered fluorescence of the paint at that point
- pressure distributions can also be conveniently measured by the use of pressure-sensitive pressure belts, a recent development in which multiple ultra-miniaturized pressure sensor modules are integrated into a flexible strip. The strip is attached to the aerodynamic surface with tape, and it sends signals depicting the pressure distribution along its surface.
- pressure distributions on a test model can also be determined by performing a **wake survey**, in which either a single pitot tube is used to obtain multiple readings downstream of the test model, or a multiple-tube manometer is mounted downstream and all its readings are taken (often by photograph).

History of wind tunnels

The First Wind Tunnels

English military engineer and mathematician Benjamin Robins (1707–1751) invented a whirling arm apparatus to determine drag and did some of the first experiments in aviation theory.

Sir George Cayley (1773–1857) also used a whirling arm to measure the drag and lift of various airfoils. His whirling arm was 5 feet long and attained top speeds between 10 and 20 feet per second.

However, the whirling arm does not produce a reliable flow of air impacting the test shape at a normal incidence. Centrifugal forces and the fact that the object is moving in its own wake mean that detailed examination of the airflow is difficult. Francis Herbert Wenham (1824–1908), a Council Member of the Aeronautical Society of Great Britain, addressed these issues by inventing, designing and operating the first enclosed wind tunnel in 1871. Once this breakthrough had been achieved, detailed technical data was rapidly extracted by the use of this tool. Wenham and his colleague Browning are credited with many fundamental discoveries, including the measurement of l/d ratios, and the revelation of the beneficial effects of a high aspect ratio.

Carl Rickard Nyberg used a wind tunnel when designing his *Flugan* from 1897 and onwards.

In a classic set of experiments, the Englishman Osborne Reynolds (1842–1912) of the University of Manchester demonstrated that the airflow pattern over a scale model would be the same for the full-scale vehicle if a certain flow parameter were the same in both cases. This factor, now known as the Reynolds Number, is a basic parameter in the description of all fluid-flow situations, including the shapes of flow patterns, the ease of heat transfer, and the onset of turbulence. This comprises the central scientific justification for the use of models in wind tunnels to simulate real-life phenomena. However, there are limitations on conditions in which dynamic similarity is based upon the Reynolds number alone.

Replica of the Wright brothers' wind tunnel.

German aviation laboratory, 1935

The Wright brothers' use of a simple wind tunnel in 1901 to study the effects of airflow over various shapes while developing their Wright Flyer was in some ways revolutionary. It can be seen from the above, however, that they were simply using the accepted technology of the day, though this was not yet a common technology in America.

Subsequent use of wind tunnels proliferated as the science of aerodynamics and discipline of aeronautical engineering were established and air travel and power were developed.

The US Navy in 1916 built one of the largest wind tunnels in the world at that time at the Washington Navy Yard. The inlet was almost 11 feet in diameter and the discharge part was 7 feet in diameter. A 500 hp electric motor drove the paddle type fan blades.

Wind tunnels were often limited in the volume and speed of airflow which could be delivered.

World War Two Wind Tunnels

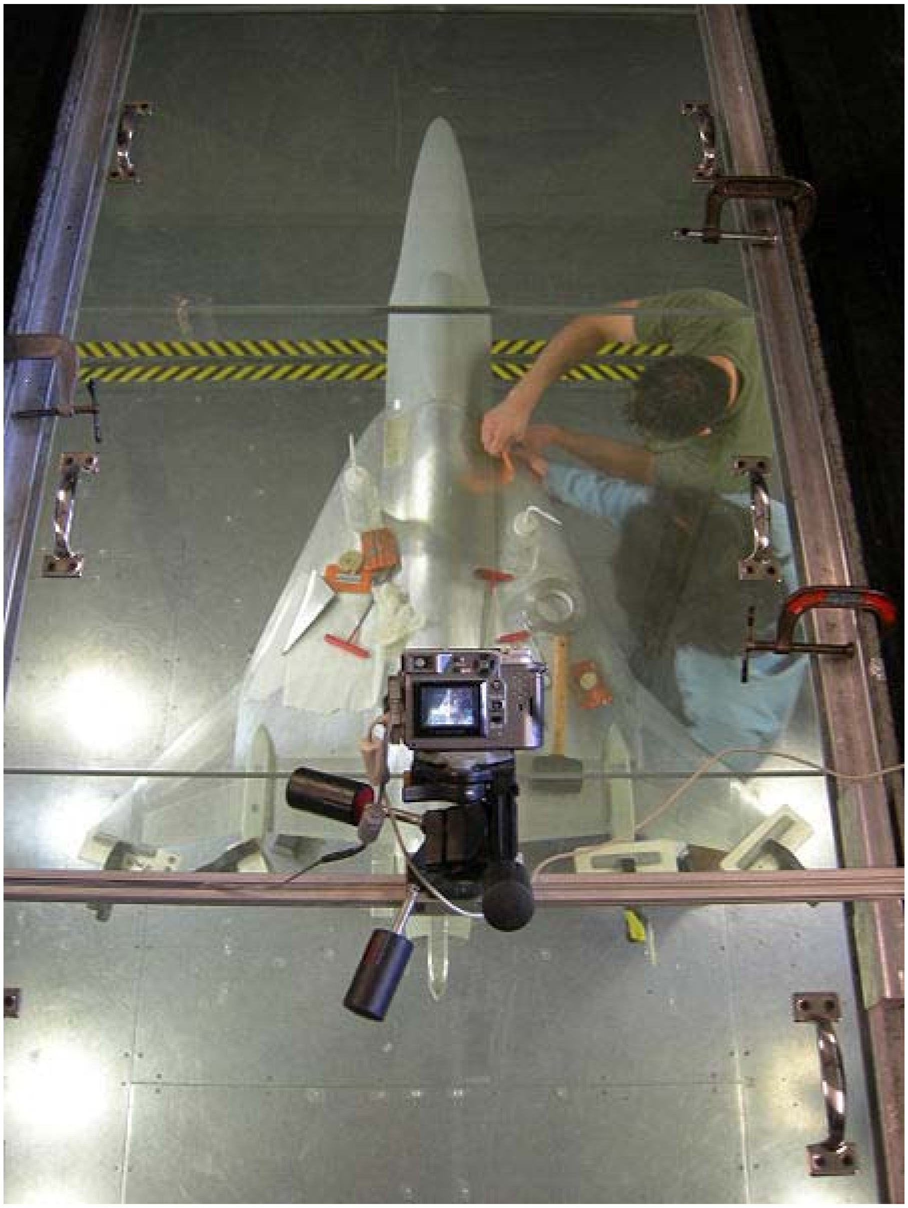
In 1941 the US constructed one of the largest wind tunnels at that time at Wright Field in Dayton, Ohio. This wind tunnel starts at 45 feet and narrows to 20 feet in diameter. Two 40 foot fans were driven by a 40,000hp electric motor. Large scale aircraft models could be tested at air speeds of 400mph.

The wind tunnel used by German scientists at Peenemünde prior to and during WWII is an interesting example of the difficulties associated with extending the useful range of large wind tunnels. It used some large natural caves which were increased in size by excavation and then sealed to store large volumes of air which could then be routed through the wind tunnels. This innovative approach allowed lab research in high-speed regimes and greatly accelerated the rate of advance of Germany's aeronautical engineering efforts. By the end of the war, Germany had at least three different *supersonic* wind tunnels, with one capable of Mach 4.4 (heated) airflows.

Post World War Two Wind Tunnels

Later research into airflows near or above the speed of sound used a related approach. Metal pressure chambers were used to store high-pressure air which was then accelerated through a nozzle designed to provide supersonic flow. The observation or instrumentation chamber ("test section") was then placed at the proper location in the throat or nozzle for the desired airspeed.

For limited applications, Computational fluid dynamics (CFD) can augment or possibly replace the use of wind tunnels. For example, the experimental rocket plane SpaceShipOne was designed without any use of wind tunnels. However, on one test, flight threads were attached to the surface of the wings, performing a wind tunnel type of test during an actual flight in order to refine the computational model. It should be noted that, for situations where external turbulent flow is present, CFD is not practical due to limitations in present day computing resources. For example, an area that is still much too complex for the use of CFD is determining the effects of flow on and around structures, bridges, terrain, etc.



Preparing a model in the Kirsten Wind Tunnel, a subsonic wind tunnel at the University of Washington

The most effective way to simulative external turbulent flow is through the use of a boundary layer wind tunnel.

There are many applications for boundary layer wind tunnel modeling. For example, understanding the impact of wind on high-rise buildings, factories, bridges, etc. can help building designers construct a structure that stands up to wind effects in the most efficient manner possible. Another significant application for boundary layer wind tunnel modeling is for understanding exhaust gas dispersion patterns for hospitals, laboratories, and other emitting sources. Other examples of boundary layer wind tunnel applications are assessments of pedestrian comfort and snow drifting. Wind tunnel modeling is accepted as a method for aiding in Green building design. For instance, the use of boundary layer wind tunnel modeling can be used as a credit for Leadership in Energy and Environmental Design (LEED) certification through the U.S. Green Building Council.

Fan blades of Langley Research Center's 16 foot transonic wind tunnel in 1990, before it was mothballed in 2004.

Wind tunnel tests in a boundary layer wind tunnel allow for the natural drag of the Earth's surface to be simulated. For accuracy, it is important to simulate the mean wind speed profile and turbulence effects within the atmospheric boundary layer. Most codes and standards recognize that wind tunnel testing can produce reliable information for designers, especially when their projects are in complex terrain or on exposed sites.

In the USA many wind tunnels have been decommissioned in the last 20 years, including some historic facilities. Pressure is brought to bear on remaining wind tunnels due to declining or erratic usage, high electricity costs, and in some cases the high value of the real estate upon which the facility sits. On the other hand CFD validation still requires wind-tunnel data, and this is likely to be the case for the foreseeable future. Studies have been conducted and others are under way to assess future military and commercial wind tunnel needs, but the outcome remains uncertain. More recently an increasing use of jetpowered, instrumented unmanned vehicles ["research drones"] have replaced some of the traditional uses of wind tunnels

How it works

Six-element external balance below the Kirsten Wind Tunnel

Air is blown or sucked through a duct equipped with a viewing port and instrumentation where models or geometrical shapes are mounted for study. Typically the air is moved through the tunnel using a series of fans. For very large wind tunnels several meters in diameter, a single large fan is not practical, and so instead an array of multiple fans are used in parallel to provide sufficient airflow. Due to the sheer volume and speed of air movement required, the fans may be powered by stationary turbofan engines rather than electric motors.

The airflow created by the fans that is entering the tunnel is itself highly turbulent due to the fan blade motion (when the fan is **blowing** air into the test section - when it is **sucking** air out of the test section downstream, the fan-blade turbulence is not a factor), and so is not directly useful for accurate measurements. The air moving through the tunnel needs to be relatively turbulence-free and laminar. To correct this problem, closely-spaced vertical and horizontal air vanes are used to smooth out the turbulent airflow before reaching the subject of the testing.

Due to the effects of viscosity, the cross-section of a wind tunnel is typically circular rather than square, because there will be greater flow constriction in the corners of a square tunnel that can make the flow turbulent. A circular tunnel provides a smoother flow.

The inside facing of the tunnel is typically as smooth as possible, to reduce surface drag and turbulence that could impact the accuracy of the testing. Even smooth walls induce some drag into the airflow, and so the object being tested is usually kept near the center of the tunnel, with an empty buffer zone between the object and the tunnel walls. There are correction factors to relate wind tunnel test results to open-air results.

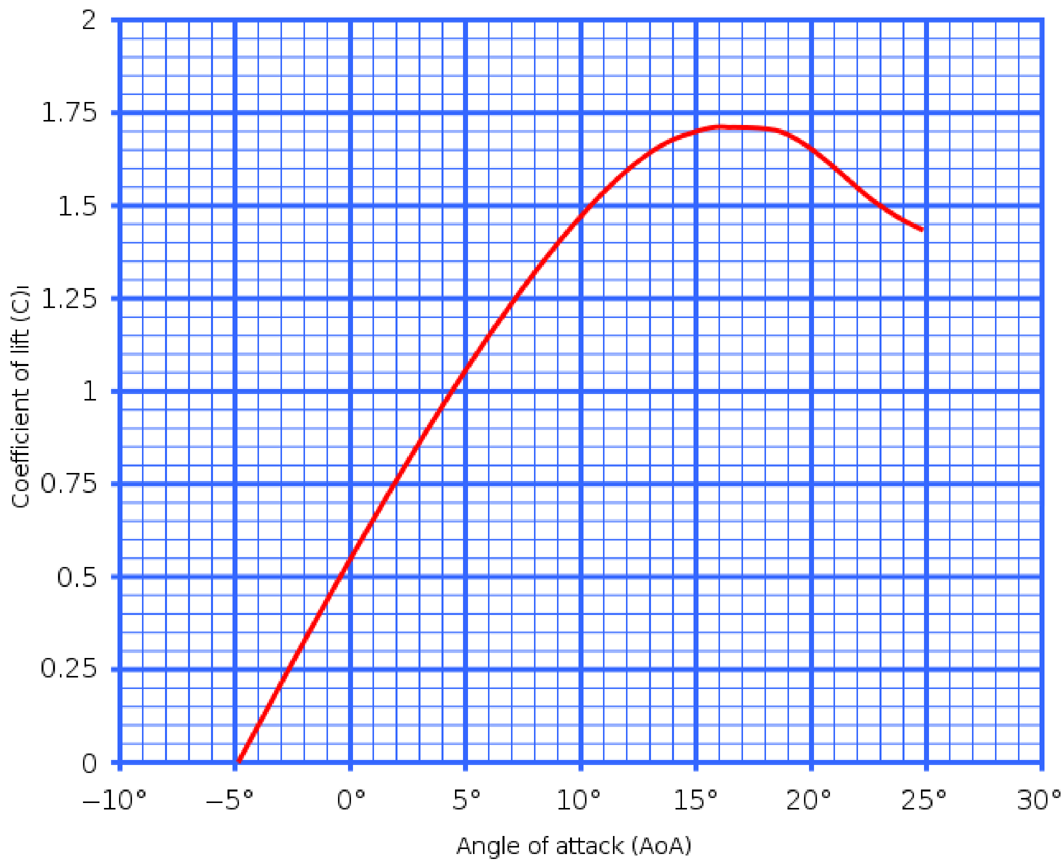
Lighting is usually recessed into the circular walls of the tunnel and shines in through windows. If the light were mounted on the inside surface of the tunnel in a conventional manner, the light bulb would generate turbulence as the air blows around it. Similarly, observation is usually done through transparent portholes into the tunnel. Rather than simply being flat discs, these lighting and observation windows may be curved to match the cross-section of the tunnel and further reduce turbulence around the window.

Various techniques are used to study the actual airflow around the geometry and compare it with theoretical results, which must also take into account the Reynolds number and Mach number for the regime of operation.

Pressure measurements

Pressure across the surfaces of the model can be measured if the model includes pressure taps. This can be useful for pressure-dominated phenomena, but this only accounts for normal forces on the body.

Force and moment measurements



A typical lift coefficient versus angle of attack curve.

With the model mounted on a force balance, one can measure lift, drag, lateral forces, yaw, roll, and pitching moments over a range of angle of attack. This allows one to produce common curves such as lift coefficient versus angle of attack (shown).

Note that the force balance itself creates drag and potential turbulence that will affect the model and introduce errors into the measurements. The supporting structures are therefore typically smoothly shaped to minimize turbulence.

Flow visualization

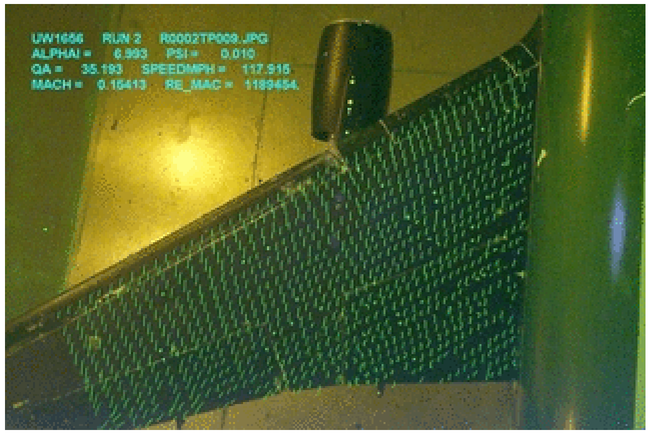
Because air is transparent it is difficult to directly observe the air movement itself. Instead, multiple methods of both quantitative and qualitative flow visualization methods have been developed for testing in a wind tunnel.

Qualitative methods

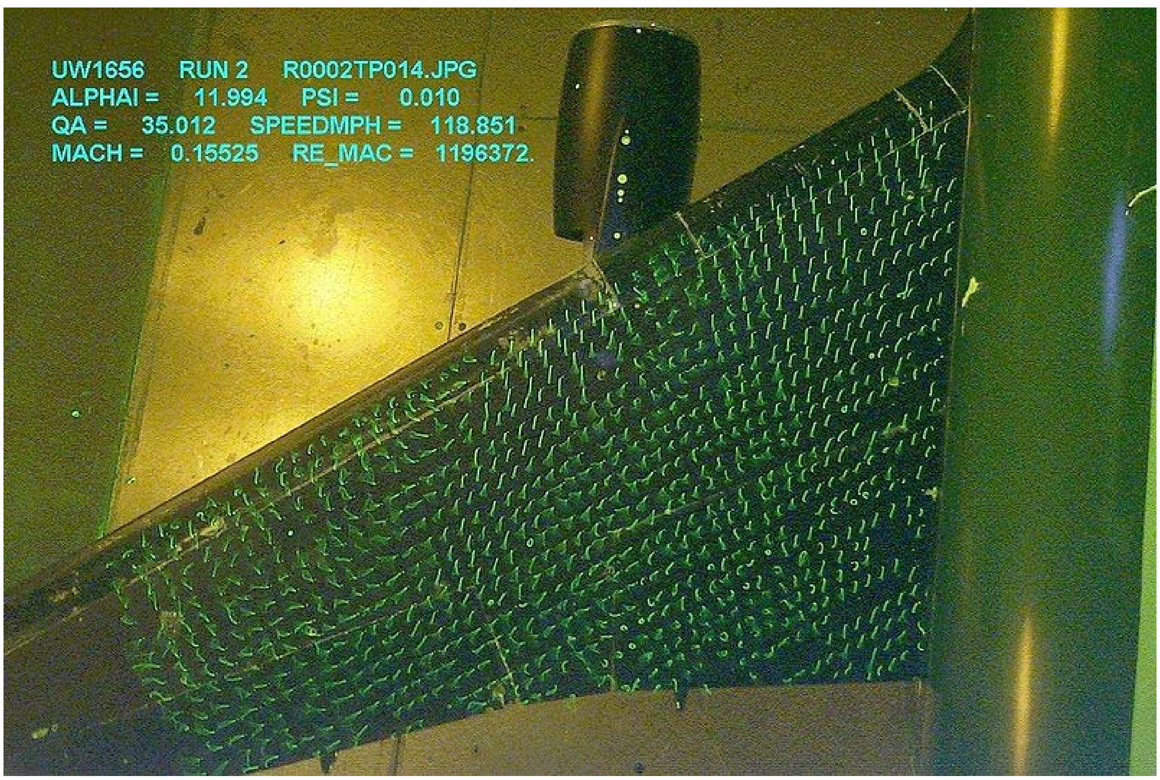
- Smoke

- Tufts

Tufts are applied to a model and remain attached during testing. Tufts can be used to gauge air flow patterns and flow separation.



Compilation of images taken during an alpha run starting at 0 degrees alpha ranging to 26 degrees alpha. Images taken at the Kirsten Wind Tunnel using fluorescent mini-tufts. Notice how separation starts at the outboard wing and progresses inward. Notice also how there is delayed separation aft of the nacelle.



Fluorescent mini-tufts attached to a wing in the Kirsten Wind Tunnel showing air flow direction and separation. Angle of attack ~ 12 degrees, speed ~120 Mph.

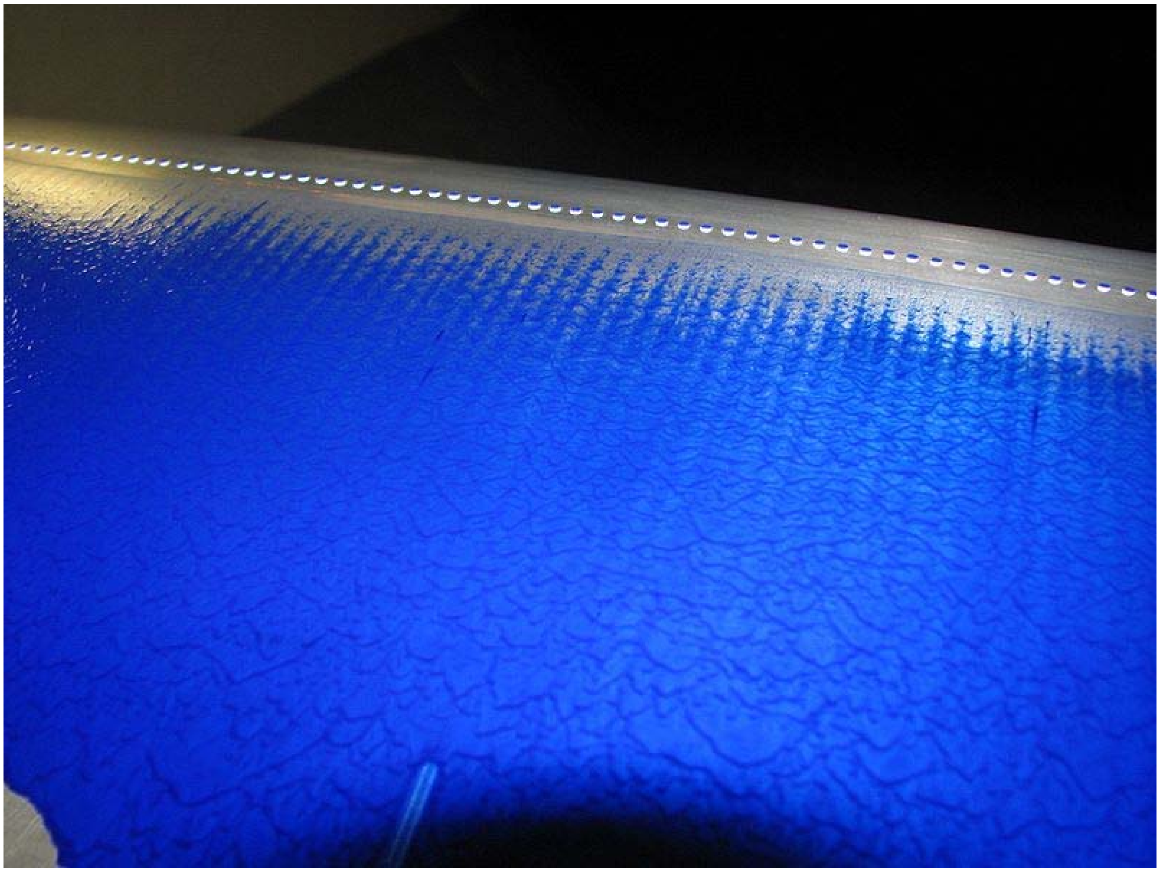
- Evaporating suspensions

Evaporating suspensions are simply a mixture of some sort or fine powder, talc, or clay mixed into a liquid with a low latent heat of evaporation. When the wind is turned on the liquid quickly evaporates leaving behind the clay in a pattern characteristic of the air flow.

China clay on a wing in the Kirsten Wind Tunnel showing reverse and span-wise flow.

- Oil

When oil is applied to the model surface it can clearly show the transition from laminar to turbulent flow as well as flow separation.



Oil flow vis on straight wing in the Kirsten Wind Tunnel. Trip dots can be seen near the leading edge.

- Sublimation

If the air movement in the tunnel is sufficiently non-turbulent, a particle stream released into the airflow will not break up as the air moves along, but stay together as a sharp thin line. Multiple particle streams released from a grid of many nozzles can provide a dynamic three-dimensional shape of the airflow around a body. As with the force balance, these injection pipes and nozzles need to be shaped in a manner that minimizes the introduction of turbulent airflow into the airstream.

High-speed turbulence and vortices can be difficult to see directly, but strobe lights and film cameras or high-speed digital cameras can help to capture events that are a blur to the naked eye.

High-speed cameras are also required when the subject of the test is itself moving at high speed, such as an airplane propeller. The camera can capture stop-motion images of how the blade cuts through the particulate streams and how vortices are generated along the trailing edges of the moving blade.

Wind tunnel classification

There are many different kinds of wind tunnels, an overview is given in the figure below:

- Low speed wind tunnel
- High speed wind tunnel
- Supersonic wind tunnel
- Hypersonic wind tunnel
- Subsonic and transonic wind tunnel

List of wind tunnels

- Modine Wind Tunnels, Climatic Wind Tunnel Testing, Large Truck and Automotive
- AeroDyn Wind Tunnel, Full Scale NASCAR Racecars
- A2 Wind Tunnel, Full scale general purpose
- Eight-Foot High Speed Tunnel
- Full Scale 30- by 60-Foot Tunnel
- Trisonic Wind Tunnel
- Unitary Plan Wind Tunnel
- Wind Shear's Full Scale, Rolling Road, Automotive Wind Tunnel
- Variable Density Tunnel

Vertical wind tunnel T-105 at TsAGI used for aircraft testing (built in 1941)

Aquadynamic Flume

The aerodynamic principles of the wind tunnel work equally on watercraft, except the water is more viscous and so imposes a greater forces on the object being tested. A looping flume is typically used for underwater aquadynamic testing. The interaction between 2 different types of fluids means that pure windtunnel testing is only partly relevant. However, a similar sort of research is done in a towing tank

Low-speed Oversize Liquid Testing

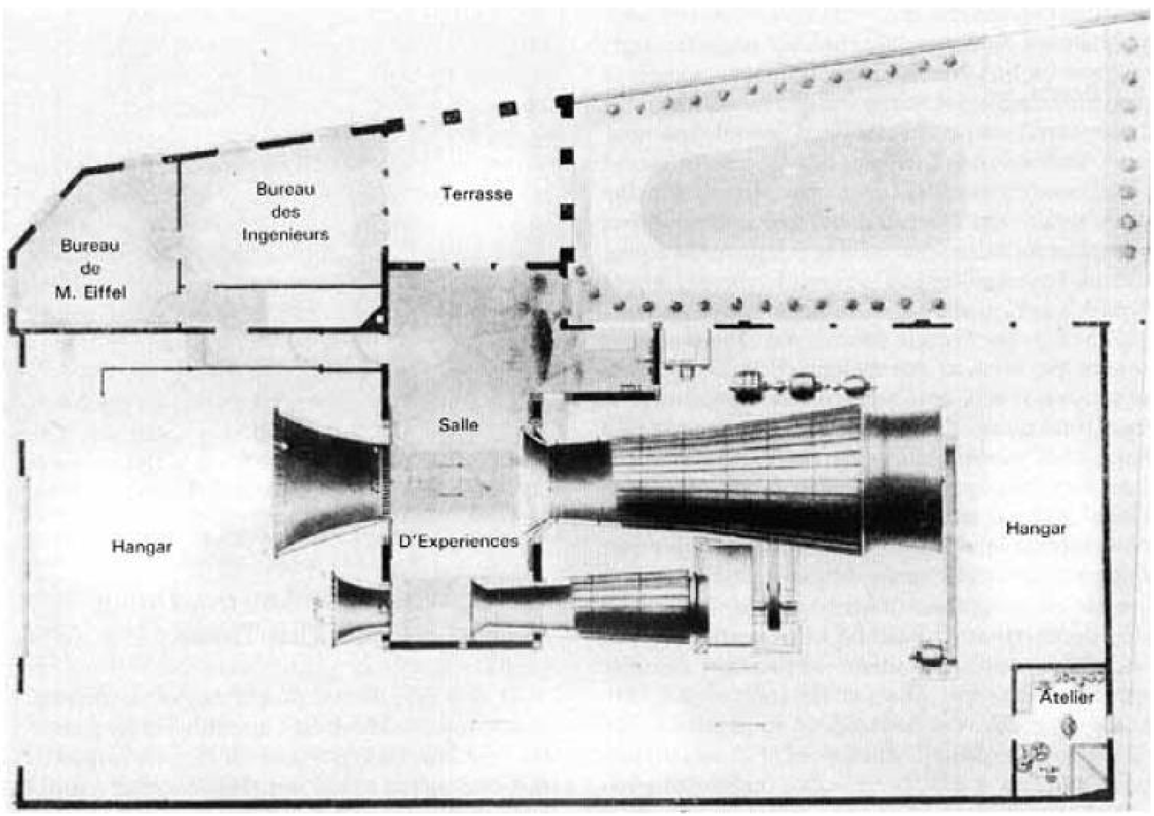
Air is not always the best test medium to study small-scale aerodynamic principles, due to the speed of the air flow and airfoil movement. A study of fruit fly wings designed to understand how the wings produce lift was performed using a large tank of mineral oil and wings 100 times larger than actual size, in order to slow down the wing beats and make the vortices generated by the insect wings easier to see and understand.

Wind Tunnel Testing for Wind Engineering

In Wind Engineering, Wind Tunnel Tests are often used to measure the velocity around, and forces or pressures upon structures. Usually very tall buildings, buildings with unusual or complicated shapes (such as a tall building with a parabolic or a hyperbolic shape), cable suspension bridges or cable stayed bridges are analysed in specialized atmospheric boundary layer wind tunnels. These feature a long upwind section to accurately represent the wind speed and turbulence profile acting on the structure. Wind tunnel tests provide the necessary design pressure measurements for use in the dynamic analysis of the structure.

Chapter 3

Subsonic and Transonic Wind Tunnel

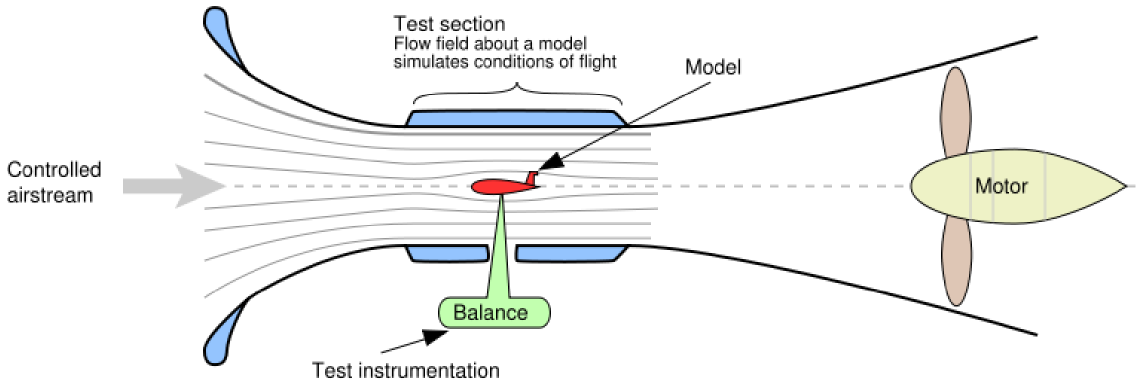


Eiffel wind tunnel

Subsonic tunnel

Low speed wind tunnels are used for operations at very low mach number, with speeds in the test section up to 400 km/h (~ 100 m/s, M = 0.3). They are of open-return type (see figure below), or return flow (see figure below). The air is moved with a propulsion system made of a large axial fan that increases the dynamic pressure to overcome the viscous losses.

Open wind tunnel



Schematic of Eiffel type open wind tunnel.

The working principle is based on the continuity and Bernoulli's equation:

The continuity equation is given by:

$$AV = constant \Rightarrow \frac{dA}{A} = -\frac{dV}{V}$$

The Bernoulli equation states:

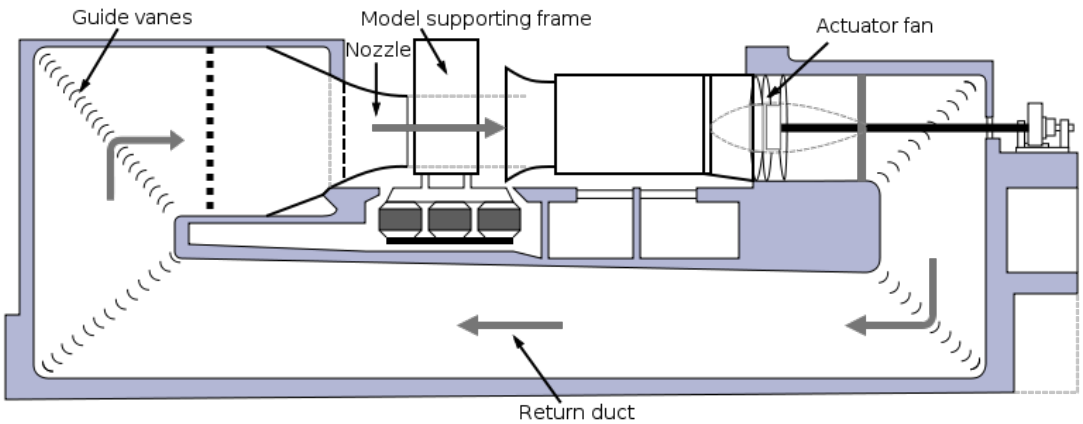
$$P_{total} = P_{static} + P_{dynamic} = P_s + \frac{1}{2}\rho V^2$$

Putting Bernoulli into the continuity equation gives:

$$V_m^2 = 2\frac{C^2}{C^2-1}\frac{P_{settl} - p_m}{\rho} \approx 2\frac{\Delta p}{\rho}$$

The contraction ratio of a windtunnel can now be calculated by: $C = \frac{A_{settl}}{A_m}$

Closed wind tunnel



Closed circuit or return flow low speed wind tunnel.

In a return-flow wind tunnel the return duct must be properly designed to reduce the pressure losses and to ensure smooth flow in the test section. The compressible flow regime: Again with the continuity law, but now for isentropic flow gives:

$$-\frac{d\rho}{\rho} = -\frac{1}{a^2}\frac{dp}{\rho} = -\frac{1}{a^2}\frac{-\rho V dV}{\rho} = \frac{V}{a^2}dV$$

The 1-D area-velocity is known as:

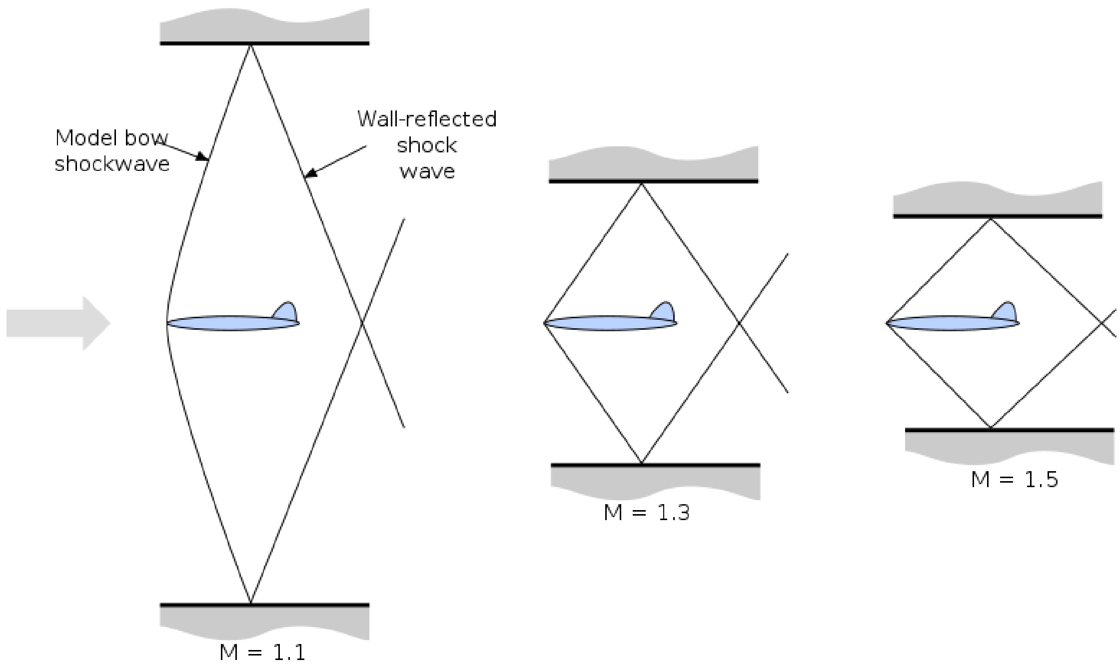
$$\frac{dA}{A} = (M^2 - 1)\frac{dV}{V}$$

The minimal area A where M=1, also known as the *sonic throat* area is than given for a perfect gas:

$$\left(\frac{A}{A_{throat}}\right)^2 = \frac{1}{M^2}\left(\frac{2}{\gamma+1}\left(1+]]\frac{\gamma-1}{2}M^2\right)\right)^{\frac{\gamma+1}{\gamma-1}}$$

Transonic tunnel

High subsonic wind tunnels (0.4 < M < 0.75) or transonic wind tunnels (0.75 < M < 1.2) are designed on the same principles as the subsonic wind tunnels. Transonic wind tunnels are able to achieve speeds close to the speeds of sound. The highest speed is reached in the test section. The Mach number is approximately one with combined subsonic and supersonic flow regions. Testing at transonic speeds presents additional problems, mainly due to the reflection of the shock waves from the walls of the test section. Therefore, perforated or slotted walls are required to reduce shock reflection from the walls. Since important viscous or inviscid interactions occur (such as shock waves or boundary layer interaction) both Mach and Reynolds number are important and must be properly simulated. Large scale facilities and/or pressurized or cryogenic wind tunnels are used.



de Laval nozzle

With a sonic throat, the flow can be accelerated or slowed down. This follows from the 1-D area-Velocity equation. If an acceleration to supersonic flow is required, a convergent-divergent nozzle is required. Otherwise:

- Subsonic (M < 1) then $\frac{dA}{dx} < 0 \Rightarrow$ converging
- Sonic throat (M = 1) where $\frac{dA}{dx} = 0$
- Supersonic (M >1) then $\frac{dA}{dx} > 0 \Rightarrow$ diverging

Conclusion: The Mach number is controlled by the expansion ratio $\frac{A}{A_{throat}}$

Chapter 4

Vertical Wind Tunnel & Supersonic Wind Tunnel

Vertical Wind Tunnel

Non-recirculating indoor vertical wind tunnel.

A **vertical wind tunnel** (VWT) is a wind tunnel which moves air up in a vertical column. It is a recreational wind tunnel, frequently advertised as "indoor skydiving" or "bodyflight". It is also a popular training tool for skydivers.

Vertical wind tunnels enable human beings to fly in air without planes or parachutes, through the force of wind being generated vertically. Wind moves upwards at approximately 195 km/h (120 mph or 55 m/s), the terminal velocity of a falling human body belly-downwards, although this can vary from person to person. A vertical wind tunnel is frequently called 'indoor skydiving' due to the popularity of vertical wind tunnels among skydivers, who report that the sensation is extremely similar to skydiving. The human body 'floats' in midair in a vertical wind tunnel, and this is called 'bodyflight' or 'body flight'.

Bodyflight

Bodyflight, or 'body flight', is the art of 'flying your body' in a controlled manner. This include turns, rolls, lateral movement, fall rate control, and other acrobatics in the air. The skill of bodyflight makes it possible for skydivers to fly closer to each other while they are falling, to allow them to link together in formation skydiving, then fly apart to a safe distance before opening parachutes. Many skills of bodyflight can be learned in a vertical wind tunnel, to enable skydivers to become better at controlling their bodies in the sky.

Bodyflight is accomplished via increasing/decreasing the drag of your body, using arms and legs as rudders for bodyflight motion control, as well as other techniques similar to that of an airplane. Professional athletes who fly through the air for long distances, such as ski jumping, have also used certain bodyflight techniques to increase jumping distance by manipulating their bodies to be more airfoil-like. Frequent visitors to a vertical wind tunnel are often called 'tunnel rats', much like frequent visitors to ski slopes are called 'ski bums'.

Some of body flying enthusiasts are developing their tunnel flying skills not for sky diving training. The goal of them is to end up with professional performances. AERODIUM Latvia has a group of professional performers -air acrobats. This team started with a performance in closing ceremony of Winter Olympics 2006 and now is performing on mobile and stationary vertical wind tunnels all around the world.

Vertical wind tunnel types

Recirculating indoor vertical wind tunnel.

All vertical wind tunnels can be classified as follows:

- Vertical wind tunnels with outdoor or open air flying experience.
- Indoor wall-to-wall flying experience vertical wind tunnels.
- Hybrid -custom made wind tunnels where wall to wall and open air experience is combined in one technology.

Outdoor vertical wind tunnels can either be stationary or portable. Portable vertical wind tunnels are often used in movies, demonstrations and are often rented for large events such as conventions & state fairs. Portable units offer a dramatic effect for the flying person and the spectators, because there are no walls around the flight area. These vertical wind tunnels allow you to fly with a full or partial outdoor/sky view. Outdoor vertical wind tunnels may also have walls or netting around the wind column, to keep beginner tunnel flyers from falling out of the tunnel.

Indoor vertical wind tunnels include recirculating and non-recirculating types. Non-recirculating vertical wind tunnels typically suck air through inlets near the bottom of the building, through the bodyflight area, and exhaust through the top of the building.

Recirculating windtunnels, form an aerodynamic loop with turning vanes, similar to a scientific wind tunnel, but using a vertical loop with a bodyflight chamber within a vertical part of the loop. Recirculating windtunnels are usually built in climates that are too cold for non-recirculating wind tunnels. The airflow of an indoor vertical wind tunnel is usually smoother and more controlled than that of an outdoor unit. Indoor tunnels are more temperature-controllable, so they are operated year-round even in cold climates.

Various propellers and fan types can be used as the mechanism to move air through a vertical wind tunnel. Motors can either be diesel-powered or electric-powered, and typically provide a vertical column of air between 6 and 16 feet wide. A control unit allows for air speed adjustment by a controller in constant view of the flyers. The controller can turn the air up for extra lift or down for less lift depending on the size, skill level, and needs of the tunnel flyer.

Safety & market appeal

Indoor skydiving also appeals to the mass market audience that are afraid of heights, since in a vertical wind tunnel, one only floats a few feet above trampoline-type netting. Wind speed can be adjusted at many vertical wind tunnels, usually between 80 and 150 mph, to accommodate the abilities of an individual and to compensate for variable body drag during advanced acrobatics. Indoor vertical wind tunnels contain the person within a chamber through the use of walls. Outdoor vertical wind tunnels have either netting or inflatable cushions surrounding the airstream, to catch anyone falling out of the airstream. While wind tunnel flying is considered a low impact activity, it does exert some strain on the flier's back, neck, and shoulders. Therefore, people with prior shoulder dislocations or back/neck problems should check with a medical professional first. While actual skydiving out of an aircraft is subject to age limitations which vary from country to country and even from state to state, bodyflying has no set lower or upper limits. Children can fly providing they are happy and are not being pressed to participate, and providing they have signed parental/guardian consent.

History

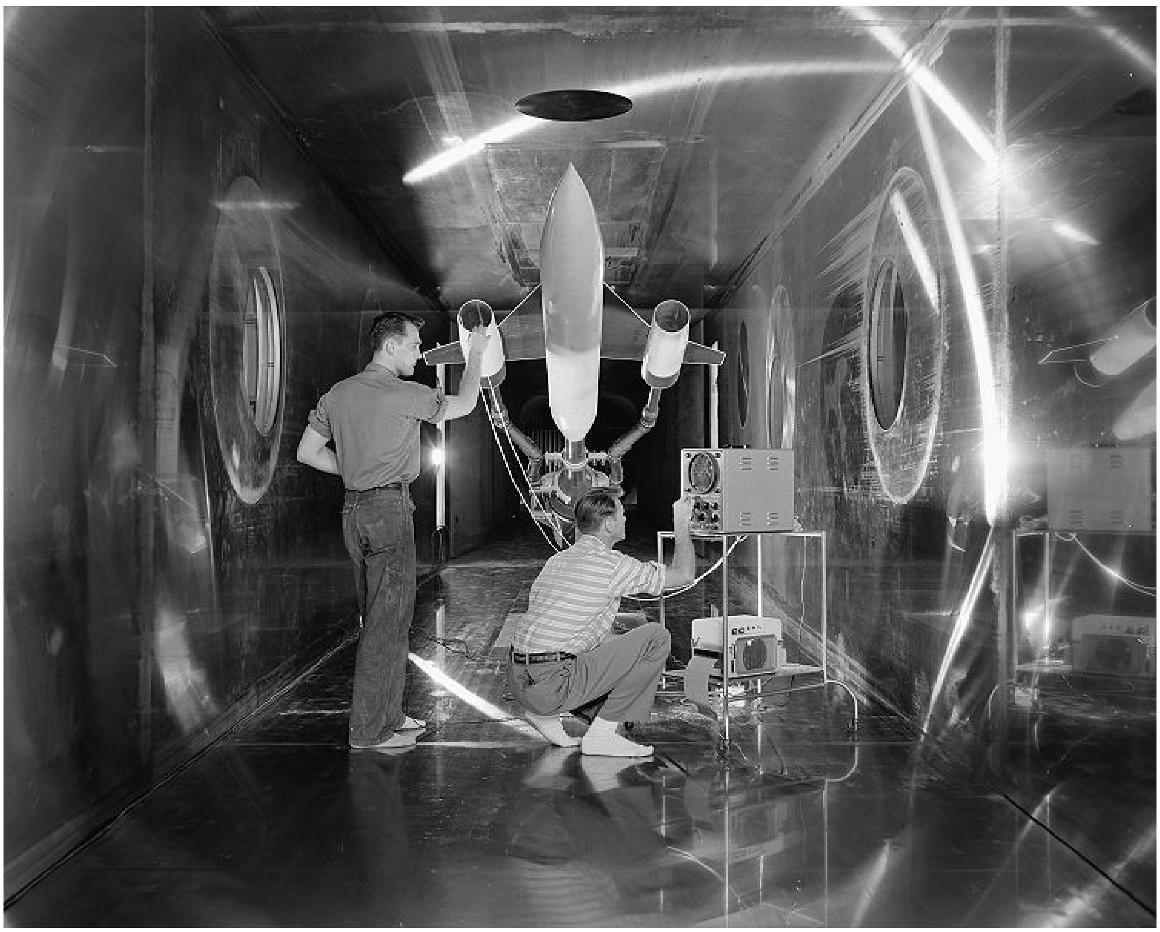
The first human to fly in a vertical wind tunnel was Jack Tiffany in 1964 at Wright Patterson Air Force Base located in Greene and Montgomery County, Ohio.

The first recreational vertical wind tunnel was developed by a Canadian company named AERODIUM in Quebec. It was developed and patented as the "Levitationarium" by Jean St. Germain in 1979. In 1982 St. Germain sold his concept and helped build two wind tunnels in America. The first vertical wind tunnel, built solely for a commercial use, opened the summer of 1982 in Las Vegas, Nevada. Later that same year, a second wind tunnel opened in Pigeon Forge, TN. Both facilities opened and operated under the name of Flyaway Indoor Skydiving until 2005 when 15-year Flyaway Manager Keith Fields purchased the Las Vegas facility and later renamed it "Vegas Indoor Skydiving".

An important milestone in vertical wind tunnel history was 'Wind Machine' at the closing ceremonies of the 2006 Torino Winter Olympics . This was a custom-built unit by AERODIUM (Latvia/Canada) for the sole purpose of the closing ceremony. Many people had never seen a vertical wind tunnel before, and were fascinated by the flying humans with no wires to keep them aloft.

A vertical wind tunnel performance at the Red Square was shown in 2009 during the presentation of logotype of Sochi 2014 Winter Olympics. In 2010, a vertical wind tunnel has been shown at the Expo 2010 in Shanghai, China.

Supersonic Wind Tunnel



Engineers check an aircraft model before a test run in the Supersonic Wind Tunnel at Lewis Flight Propulsion Laboratory.

A **supersonic wind tunnel** is a wind tunnel that produces supersonic speeds ($1.2<M<5$) The Mach number and flow are determined by the nozzle geometry. The Reynolds number is varied changing the density level (pressure in the settling chamber). Therefore a high pressure ratio is required (for a supersonic regime at $M=4$, this ratio is of the order of 10). Apart from that, condensation or liquefaction can occur. This means that a supersonic wind tunnel needs a drying or a pre-heating facility. A supersonic wind tunnel has a large power demand leading to only intermittent operation.

Restrictions for supersonic tunnel operation

Minimum required pressure ratio

Optimistic estimate: Pressure ratio $\leq$ the total pressure ratio over normal shock at M in test section:

$$\frac{P_t}{P_{amb}} \leq \left(\frac{P_{t_1}}{P_{t_2}}\right)_{M_1=M_m}$$

Examples:

Temperature effects: condensation

Temperature in the test section:

$$\frac{T_m}{T_t} = \left(1 + \frac{\gamma - 1}{2} M_m^2\right)^{-1}$$

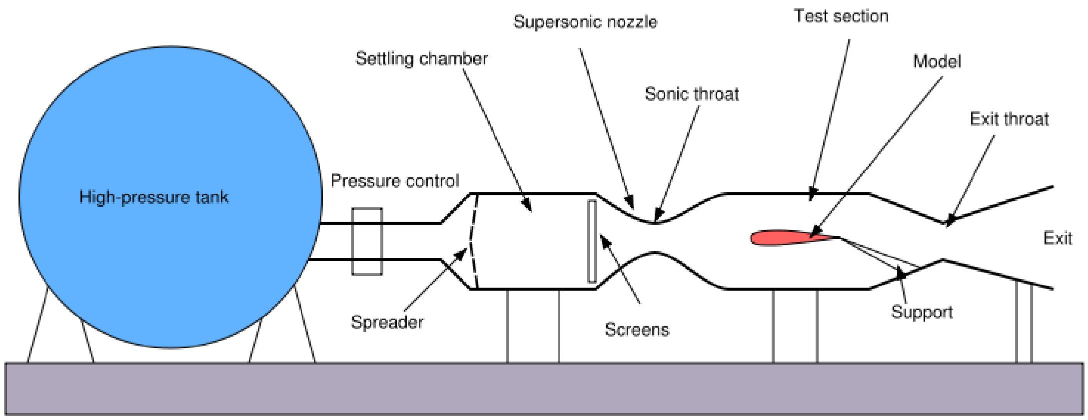
with T_t = 330K: T_m = 70K at M_m = 4

The Mach range is limited by reservoir temperature

Power requirements

The power required to run a supersonic windtunnel is enormous, of the order of 50 MW per square meter of test section. For this reason most wind tunnels operate intermittently using energy stored in high-pressure tanks. These windtunnels are also called intermittent supersonic blowdown wind tunnels (of which a schematic preview is given below). Another way of achieving the huge power output is with the use of a vacuum storage tank. These tunnels are called indraft supersonic wind tunnels. Other problems operating a supersonic wind tunnel include:

- adequate supply of dry air
- wall interference effects
- high-quality instruments capable of rapid measurements due to short run times on intermittent tunnels



Tunnels such as a Ludwieg tube have short test times (usually less than one second), relatively high Reynolds number, and low power requirements.

Chapter 5

Tunnel Boring Machine

A tunnel boring machine that was used at Yucca Mountain nuclear waste repository

A **tunnel boring machine** (**TBM**) also known as a "mole", is a machine used to excavate tunnels with a circular cross section through a variety of soil and rock strata. They can bore through hard rock, sand, and almost anything in between. Tunnel diameters can range from a metre (done with micro-TBMs) to almost 16 metres to date. Tunnels of less than a metre or so in diameter are typically done using trenchless construction methods or horizontal directional drilling rather than TBMs.

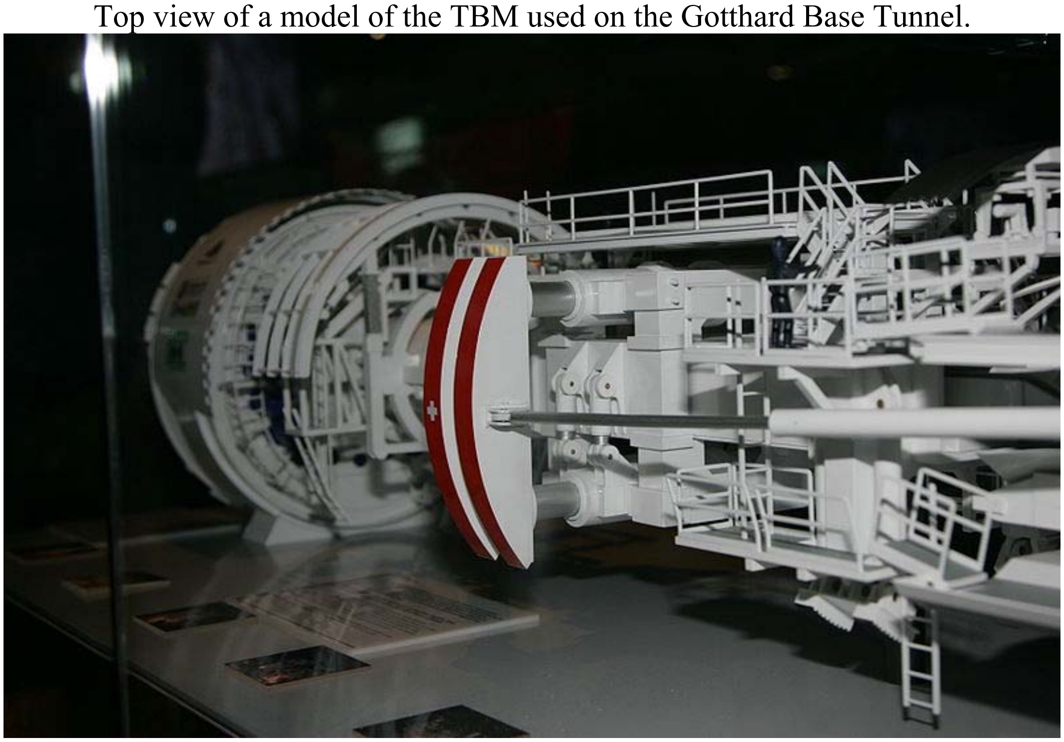
Tunnel boring machines are used as an alternative to drilling and blasting (D&B) methods in rock and conventional 'hand mining' in soil. TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the tunnel, and makes them suitable to use in heavily urbanized areas. The major disadvantage is the upfront cost. TBMs are expensive to construct, and can be difficult to transport. However, as modern tunnels become longer, the cost of tunnel boring machines versus drill and blast is actually less—this is because tunnelling with TBMs is much more efficient and results in a shorter project.

The largest diameter TBM, at 15.43 m, was built by Herrenknecht AG for a recent project in Shanghai, China. The machine was built to bore through soft ground including sand and clay. The largest diameter hard rock TBM, at 14.4 m, was manufactured by The Robbins Company for Canada's Niagara Tunnel Project. The machine is currently boring a hydroelectric tunnel beneath Niagara Falls, the machine has been named "Big Becky" in reference to the Sir Adam Beck hydroelectric dams to which it is tunneling to provide an additional hydroelectric tunnel.

History

Cutting shield used for the New Elbe Tunnel.

Top view of a model of the TBM used on the Gotthard Base Tunnel.



Looking towards the cutting shield at the hydraulic jacks.

Hydraulic jacks holding a TBM in place.

The support structures at the rear of a TBM. This machine was used to excavate the main tunnel of the Yucca Mountain nuclear waste repository in Nevada.

Tunnel boring machine at the site of Weinberg tunnell Altstetten-Zürich-Oerlikon near Zürich Oerlikon train station.

The first successful tunnelling shield was developed by Sir Marc Isambard Brunel to excavate the Thames Tunnel in 1825. However, this was only the invention of the shield concept and did not involve the construction of a complete tunnel boring machine, the digging still having to be accomplished by the then standard excavation methods.

The first boring machine reported to have been built was Henri-Joseph Maus' *Mountain Slicer*. Commissioned by the King of Sardinia in 1845 to dig the Fréjus Rail Tunnel between France and Italy through the Alps, Maus had it built in 1846 in an arms factory near Turin. It consisted of more than 100 percussion drills mounted in the front of a locomotive-sized machine, mechanically power-driven from the entrance of the tunnel. The Revolutions of 1848 affected the funding, and the tunnel was not completed until 10 years later, by using innovative but less expensive methods such as pneumatic drills..

In the United States, the first boring machine to have been built was used in 1853 during the construction of the Hoosac Tunnel. Made of cast iron, it was known as *Wilson's Patented Stone-Cutting Machine*, after inventor Charles Wilson. It drilled 10 feet into the rock before breaking down. The tunnel was eventually completed more than 20 years later, and as with the Fréjus Rail Tunnel, by using less ambitious methods.

In the early 1950s, F.K. Mitry won a dam diversion contract for the Oahe Dam in Pierre, South Dakota, and consulted with James S. Robbins, founder of The Robbins Company, to dig through what was the most difficult shale to excavate at that time, the Pierre Shale. Robbins built a machine that was able to cut 160 feet in 24 hours in the shale, ten times faster than any other method at that time.

The breakthrough that made tunnel boring machines efficient and reliable was the invention of the rotating head mounted with disc cutters. Initially, Robbins' tunnel boring machine used steel picks rotating in a circular motion to dig the excavation front, but he quickly discovered that these picks, no matter how strong they were, had to be changed frequently as they broke or tore off. By replacing the picks with longer lasting disc cutters, this problem was significantly reduced. The design was first utilized successfully at the Humber River Sewer Tunnel in 1956 (Foley, 2009). Since then, all successful hard rock tunnel boring machines have utilized rotating cutting wheels with circular disc cutters.

Description

Modern TBMs typically consist of the rotating cutting wheel, called a cutter head, followed by a main bearing, a thrust system and trailing support mechanisms. The type of machine used depends on the particular geology of the project, the amount of ground water present and other factors.

Hard rock TBMs

In hard rock, either shielded or open-type TBMs can be used. All types of hard rock TBMs excavate rock using disc cutters mounted in the cutter head. The disc cutters create compressive stress fractures in the rock, causing it to chip away from the rock in front of the machine, called the tunnel face. The excavated rock, known as muck, is transferred through openings in the cutter head to a belt conveyor, where it runs through the machine to a system of conveyors or muck cars for removal from the tunnel.

Open-type TBMs have no shield, leaving the area behind the cutter head open for rock support. To advance, the machine uses a gripper system that pushes against the side walls of the tunnel. The machine can be continuously steered while gripper shoes push on the side-walls to react the machine's forward thrust. At the end of a stroke, the rear legs of the machine are lowered, the grippers and propel cylinders are retracted. The retraction of the propel cylinders repositions the gripper assembly for the next boring cycle. The grippers are extended, the rear legs lifted, and boring begins again. The open-type, or Main Beam, TBM does not install concrete segments behind it as other machines do. Instead, the rock is held up using ground support methods such as ring beams, rock bolts, shotcrete, steel straps, and wire mesh (Stack, 1995).

In fractured rock, shielded hard rock TBMs can be used, which erect concrete segments to support unstable tunnel walls behind the machine. Double Shield TBMs are so called because they have two modes; in stable ground they can grip against the tunnel walls to advance forward. In unstable, fractured ground, the thrust is shifted to thrust cylinders that push off against the tunnel segments behind the machine. This keeps the significant thrust forces from impacting fragile tunnel walls. Single Shield TBMs operate in the same way, but are used only in fractured ground, as they can only push off against the concrete segments (Stack, 1995).

Soft ground TBMs

In soft ground, there are two main types of TBMs: Earth Pressure Balance Machines (EPB) and Slurry Shield (SS). Both types of machines operate like Single Shield TBMs, using thrust cylinders to advance forward by pushing off against concrete segments. Earth Pressure Balance Machines are used in soft ground with less than 7 bar of pressure. The cutter head does not use disc cutters only, but instead a combination of tungsten carbide cutting bits, carbide disc cutters, and/or hard rock disc cutters. The EPB gets its name because it is capable of holding up soft ground by maintaining a balance between earth and pressure. The TBM operator and automated systems keep the rate of soil removal equal to the rate of machine advance. Thus, a stable environment is maintained. In addition, additives such as bentonite, polymers and foam are injected into the ground to further stabilize it.

In soft ground with very high water pressure and large amounts of ground water, Slurry Shield TBMs are needed. These machines offer a completely enclosed working environment. Soils are mixed with bentonite slurry, which must be removed from the tunnel through a system of slurry tubes that exit the tunnel. Large slurry separation plants are needed on the surface for this process, which separate the dirt from the slurry so it can be recycled back into the tunnel.

While the use of TBMs relieves the need for large numbers of workers at high pressures, a caisson system is sometimes formed at the cutting head for slurry shield TBMs. Workers entering this space for inspection, maintenance and repair need to be medically cleared as "fit to dive" and trained in the operation of the locks.

Back-up systems

Behind all types of tunnel boring machines, inside the finished part of the tunnel, are trailing support decks known as the back-up system. Support mechanisms located on the back-up can include: conveyors or other systems for muck removal, slurry pipelines if applicable, control rooms, electrical systems, dust removal, ventilation and mechanisms for transport of pre-cast segments.

Urban tunnelling and near surface tunnelling

Urban tunnelling has the special challenge of requiring that the ground surface be undisturbed. This means that ground subsidence must be avoided. The normal method of doing this in soft ground is to maintain the soil pressures during and after the tunnel construction. There is some difficulty in doing this, particularly in varied strata (e.g., boring through a region where the upper portion of the tunnel face is wet sand and the lower portion is hard rock).

TBMs with positive face control, such as EPB and SS, are used in such situations. Both types (EPB and SS) are capable of reducing the risk of surface subsidence and voids if operated properly and if the ground conditions are well documented.

When tunnelling in urban environments, other tunnels, existing utility lines and deep foundations need to be addressed in the early planning stages. The project must accommodate measures to mitigate any detrimental effects to other infrastructure.

Chapter 6

Submerged Floating Tunnel

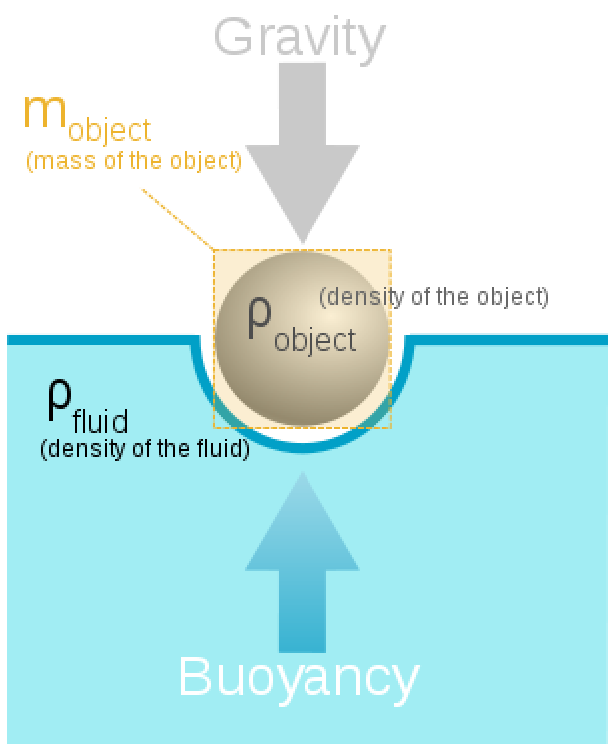
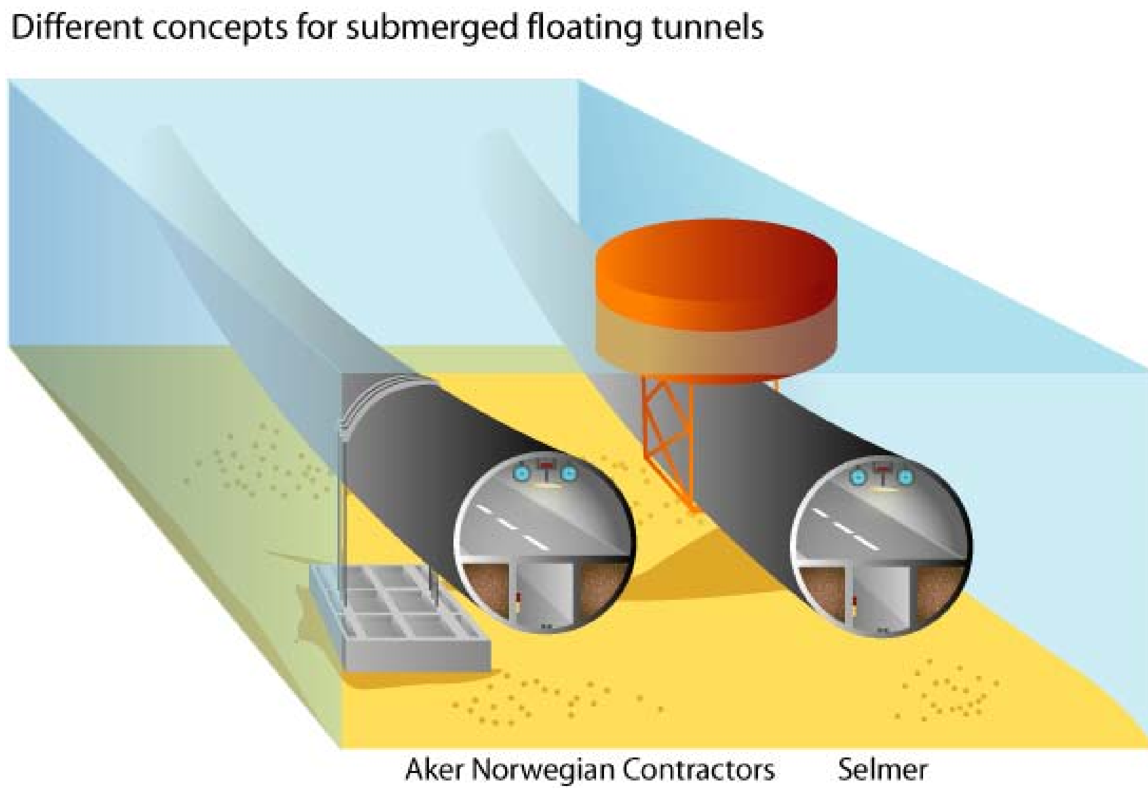


Diagram of the buoyancy effect

A **Submerged Floating Tunnel**, or **SFT** (also **suspended tunnel** or **Archimedes bridge**) is a tunnel that floats in water, supported by its buoyancy (specifically, by employing the hydrostatic thrust, or Archimedes' Principle).

The tube is placed underwater, deep enough to avoid water traffic and weather, but not so deep that high water pressure needs to be dealt with—usually 20–50 m (60–150 ft) is sufficient. Cables either anchored to the Earth or to pontoons at the surface prevent it from floating to the surface or submerging, respectively.

Construction

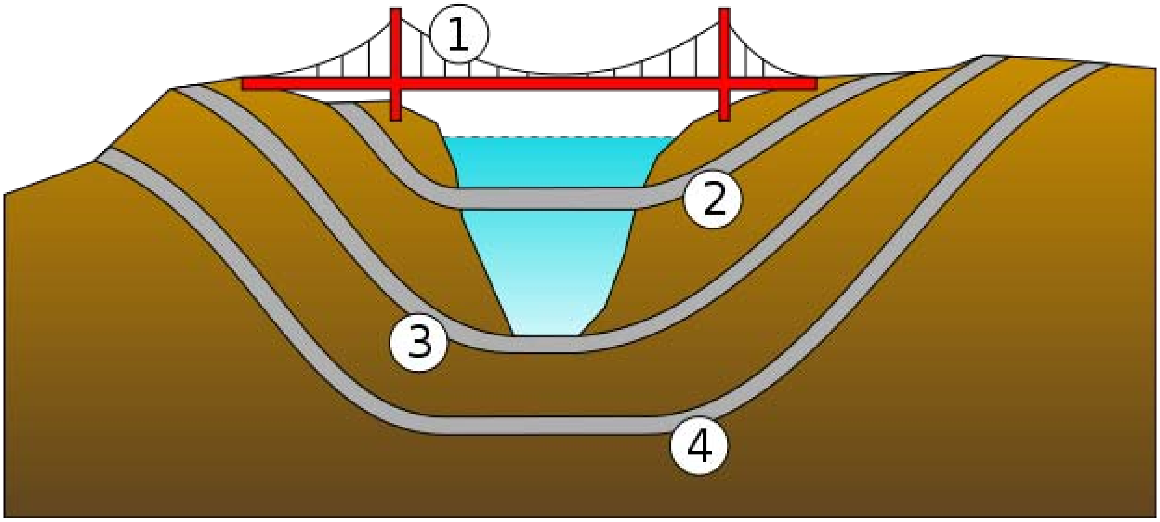


Two types of Submerged Floating tunnels

The concept of submerged floating tunnels is based on well-known technology applied to floating bridges and offshore structures, but the construction is mostly similar to that of immersed tunnels: One way is to build the tube in sections in a dry dock; then float these to the construction site and sink them into place, while sealed; and, when the sections are fixed to each other, the seals are broken. Another possibility is to build the sections unsealed, and after welding them together, pump the water out.

The ballast used is calculated so that the structure has approximate hydrostatic equilibrium (that is, the tunnel is roughly the same overall density as water), whereas immersed tube tunnels are ballasted more to weight them down to the sea bed. This, of course, means that a submerged floating tunnel must be anchored to the ground or to the water surface to keep it in place (which of these depends on which side of the equilibrium point the tunnel is).

Applications



Water spanning structures: **1**: Suspension bridge **2**: Archimedes bridge **3**: Immersed tube **4**: Undersea tunnel

Submerged floating tubes allow construction of a tunnel in extremely deep water, where conventional bridges or tunnels are technically difficult or prohibitively expensive. They would be able to deal with seismic disturbances and weather events easily (as they have some degree of freedom in regards to movement), and their structural performance is independent of length (that is, it can be very long without compromising its stability and resistance).

On the other hand, they may be vulnerable in regards to anchors or submarine traffic, which therefore has to be taken in consideration when building one.

Likely applications include fjords, deep, narrow sea channels, and deep lakes.

Proposals

A submerged floating tunnel has never been built, but several proposals have been presented by different entities.

Date	Place	Country	Proposer
late 1800s	English Channel	United Kingdom	Sir Edward James Reed
1969	Strait of Messina	Italy	Alan Grant
1998	Høgsfjord	Norway	Norwegian Public Roads Administration

April 16, 2003	Transatlantic tunnel	N/A	Discovery Channel's Extreme Engineering (Season 1, episode 3)
?	Funka Bay, Hokkaido	Japan	Society of Submerged Floating Tunnel Technology
?	Lake Washington, Seattle	United States	James Felch / Subterra
?	Vancouver Island	Canada	Ministry of Transportation of British Columbia, Canada
?	Lugano Lake	Switzerland	

Italy and China

Ponte di Archimede International, an Italian company, investigated the SFT in collaboration with the Norwegian Roads Research Laboratory, the Danish Road Institute and the Italian Shipping Register, with a financial grant from the European Union and the coordination of FEHRL (Forum European Highways Research Laboratories) an International Association of 22 Public Road Administrations. Furthermore the Provincial Administrations of Como (Como Lake) and Lecco, in Italy, have officially shown great interest in the Archimede's Bridge for crossing the Lario and the study of the submerged floating tunnel in the Strait of Messina has been promoted by Ponte di Archimede S.p.A. and verified with a feasibility analysis by the Italian Naval Register (RINA).

The SIJLAB (Sino-Italian Joint Laboratory of Archimedes' Bridge), created in 1998, between Institute of Mechanics, Chinese Academy of Sciences, China and Ponte di Archimede S.p.A., is financed by the Italian Ministry of Foreign Affairs, the Chinese Ministry of Science and Technology and the Institute of Mechanics of the Chinese Academy of Sciences.

The consortium has started to build a 100m demonstration tunnel in Qiandao Lake in China eastern province of Zhejiang. Inside it, two layers of one-way motorways will run though in the middle, with two railway tracks flanking them. The Qiandao Lake prototype will serve to help plan for the project of a 3,300-meter submerged floating tunnel in the Jintang Strait, in the Zhoushan archipelago, also situated in Zhejiang.

According to Elio Matacena, the President of Ponte Archimede di International, the only constraint to build such tunnels in deeper waters is the price of the structure. Namely, the cables, which are very expensive, would be very long. He also refers that the bridge is capable of supporting more weight than a traditional bridge, which has very strict weight limits, while being up to two times cheaper. Matacena points out that the environmental studies carried on show that the bridge would have a very low impact on the aquatic life.

Indonesia

Indonesia has also expressed interest in this technology. For the infrastructure, that would connect Bali to Thailand, there were two options, a conventional bridge or the undersea tunnel.

On 2004 the tunnel option was more widely discussed, specially when Kwik Kian Gie, then the Minister of National Development announced that a European consortium was interested in investing in the undersea tunnel between Java and Sumatra. The budget was told to be around 15 billion US dollars for the undersea tunnel in the Sunda Strait; in long term it would link up Bali, Java, Sumatra, Malaysia and Thailand in an uninterrupted chain. The project was planned to start construction in 2005 and be ready to use by 2018, and was a part of the Asian Highway.

However, the bridge option was later favored.

In 2007, Indonesian experts, led by Ir. Iskendar, Director for the Center of Assessment and Application of Technology for Transportation System and Industries, participated in a meeting with SIJLAB engineers, from the sino-Italian Archimedes Bridge project. As an archipelagic country, consisting of more than 13 thousand islands, Indonesia could benefit of such tunnels. The conventional transportation service between islands is made mainly by ferries. Archimedes bridges (Terowongan Dasar Laut, in Indonesian) could thus be an alternative to connect adjacent islands, in addition to bridges.

Chapter 7

Culvert

A large stone culvert (1888–89) in Blackwater Canyon, West Virginia. The structure formerly supported a railroad.

A **culvert** is a device used to channel water. It may be used to allow water to pass underneath a road, railway, or embankment for example. Culverts can be made of many different materials; steel, polyvinyl chloride (PVC) and concrete are the most common. Formerly, construction of stone culverts was common.

Types

Precast concrete culvert segments

Culverts come in many shapes and sizes, including round, elliptical, flat-bottomed, pear-shaped, and box. They vary from the small drainage culverts found on highways and driveways to large diameter structures on significant waterways or supporting large water control works. The latter can comprise large engineering projects.

There are three primary materials that culverts are made out of: steel, precast concrete, and polymer (plastic). They can also be built as a hybrid between steel and concrete, for example an open-bottom corrugated steel structure on concrete footings, or a corrugated steel structure with a concrete "collar" around the ends.

When boxes or pipes are placed side-by-side to create a width of greater than twenty feet, the culvert is defined as a bridge in the United States. This is a requirement of the federal bridge inspection standards and ensures that the culvert is inspected on a regular basis.

Minimum energy loss culverts

In the coastal plains of Queensland (North-East Australia), torrential rains during the wet season place a heavy demand on culverts. Further, the natural slope of the flood plains is often very small and little fall (or head loss) is permissible in the culverts. G.R. McKay and C.J. Apelt developed and patented the design procedure of minimum energy loss culverts waterways which yield small afflux. Apelt presented an authoritative review of the topic (1983) and a well-documented documentary (1994).

A minimum energy loss culvert or waterway is a structure designed with the concept of minimum head loss. The flow in the approach channel is contracted through a streamlined inlet into the barrel where the channel width is minimum, and then it is expanded in a streamlined outlet before being finally released into the downstream natural channel. Both the inlet and outlet must be streamlined to avoid significant form losses. The barrel invert is often lowered to increase the discharge capacity.

The concept of minimum energy loss culverts was developed by Norman Cottman, shire engineer in Victoria (Australia) and by Professor Gordon McKay, University of Queensland (Brisbane, Australia) during the late 1960s. While a number of small-size structures were designed and built in Victoria, some major structures were designed, tested and built in South-East Queensland.

Forestry

Winter treasure trove under the culvert on a sub zero morning

Polymer drainage culvert

In forestry, proper use of cross-drainage culverts can improve water quality while allowing forest operations to continue.

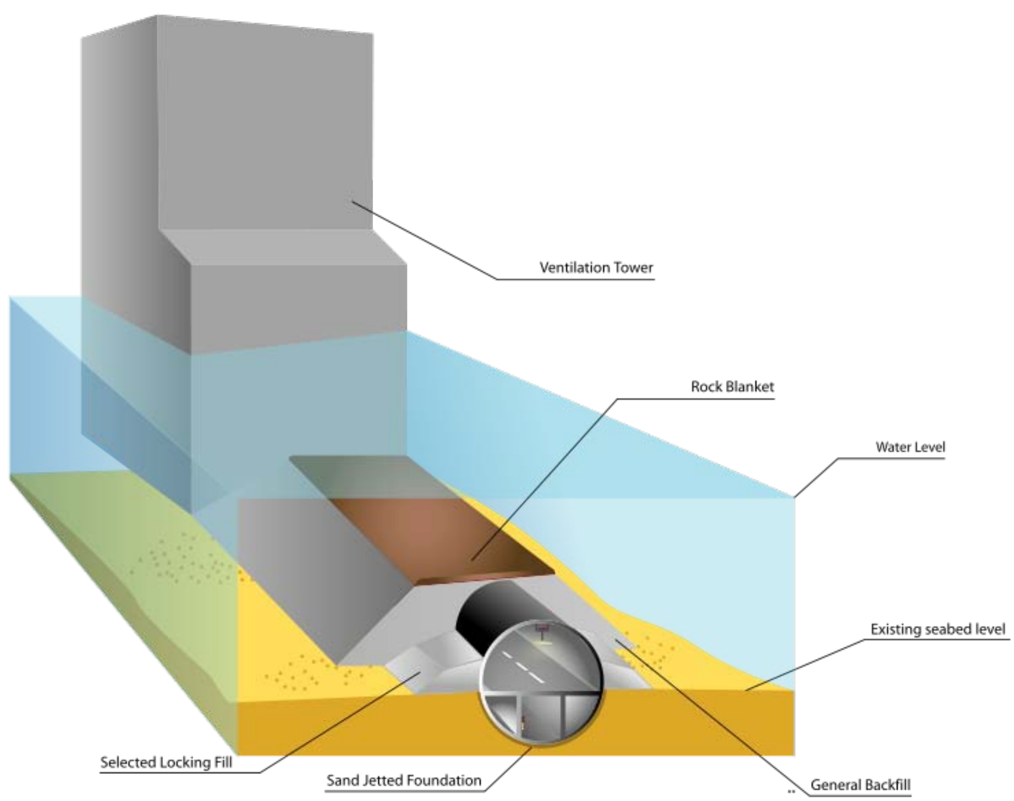
Accidents

Accidents with a culvert can occur if a flood overwhelms it and disrupts the road or railway above it, such as the Bethungra accident of 1885, which killed seven people.

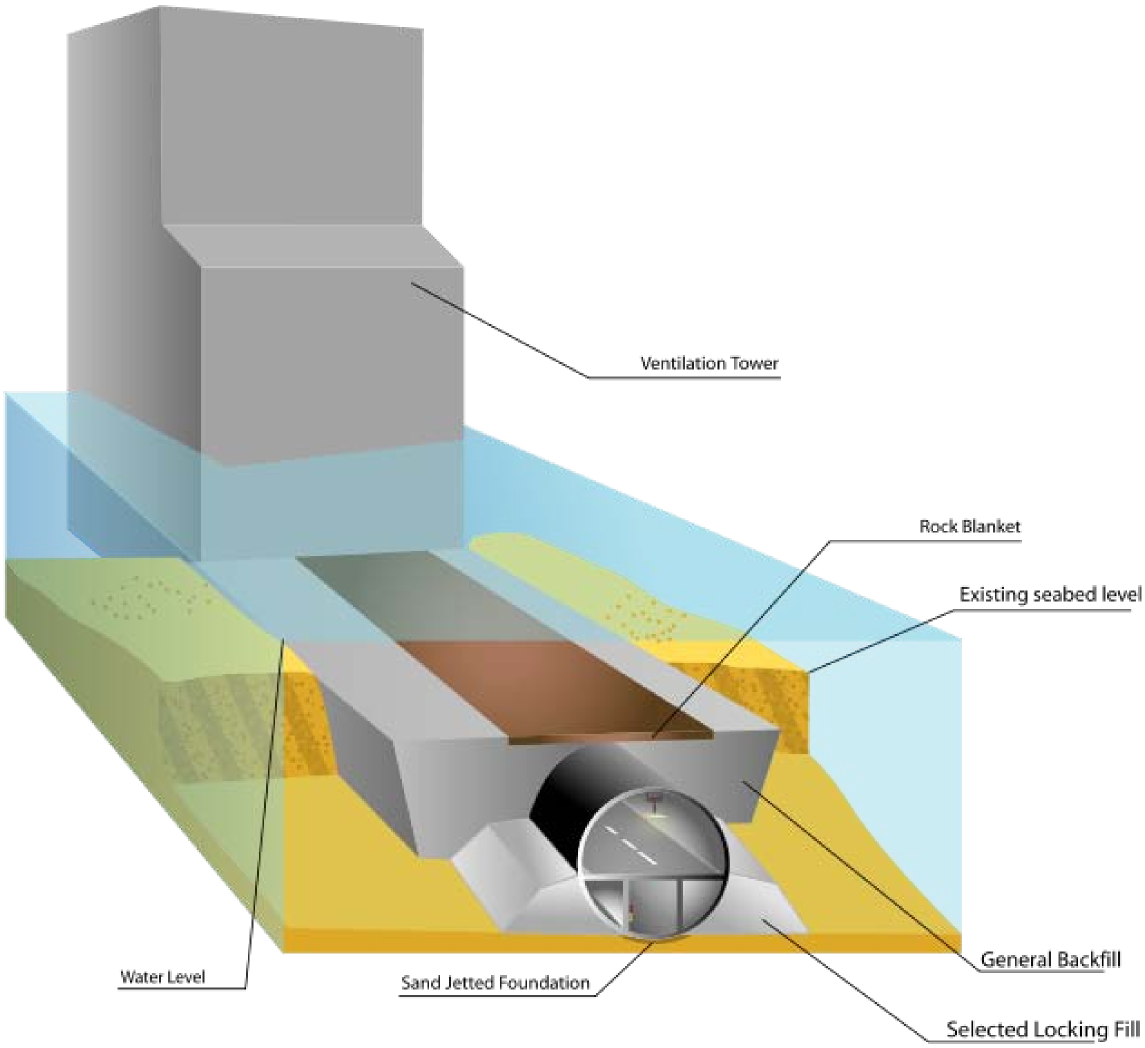
If a culvert made of steel is not properly galvanized, the culvert can eventually collapse, again disrupting the road or railway above it. This happened at a culvert near Gosford, New South Wales in 2007, killing five.

Chapter 8

Immersed Tube



Immersed tube type A, built upon a shallow trench on the seabed.



Immersed tube type B, built under the seabed level.

An **immersed tube** is a kind of underwater tunnel composed of segments, constructed elsewhere and floated to the tunnel site to be sunk into place and then linked together. They are commonly used for road and rail crossings of rivers, estuaries and sea channels/harbours. Immersed tubes are often used in conjunction with other forms of tunnel at their end, such as a cut and cover or bored tunnel, which is usually necessary to continue the tunnel from near the water's edge to the entrance (portal) at the land surface.

Construction

The Marmaray immersed tube in Istanbul, Turkey during construction.

The tunnel is made up of separate elements, each prefabricated in a manageable length, then having the ends sealed with bulkheads so they can be floated. At the same time, the corresponding parts of the path of the tunnel are prepared, with a trench on the bottom of the channel being dredged and graded to fine tolerances to support the elements. The next stage is to place the elements into place, each towed to the final location, in most cases requiring some assistance to remain buoyant. Once in position, additional weight is used to sink the element into the final location, this being a critical stage to ensure each piece is aligned correctly. After being put into place the joint between the new element and the tunnel is dewatered and then made water tight, this process continuing sequentially along the tunnel.

The trench is then backfilled and any necessary protection, such as rock armour, added over the top. The ground beside each end tunnel element will often be reinforced, to permit a tunnel boring machine to drill the final links to the portals on land. After these stages the tunnel is complete, and the internal fitout can be carried out.

The segments of the tube may be constructed in one of two methods. In the United States, the preferred method has been to construct steel or cast iron tubes which are then lined with concrete. This allows use of conventional shipbuilding techniques, with the segments being launched after assembly in dry docks. In Europe, reinforced concrete box tube construction has been the standard; the sections are cast in a basin which is then flooded to allow their removal.

Advantages and disadvantages

The main advantage of an immersed tube is that they can be considerably more cost effective than alternative options – i.e. a bored tunnel beneath the water being crossed (if indeed this is possible at all due to other factors such as the geology and seismic activity) or a bridge. Other advantages relative to these alternatives include:

- Their speed of construction
- Minimal disruption to the river/channel, if crossing a shipping route
- Resistance to seismic activity
- Safety of construction (for example, work in a dry dock as opposed to boring beneath a river)
- Flexibility of profile (although this often partly dictated by what is possible for the connecting tunnel types)

Disadvantages include:

- The tunnel is partly exposed (usually with some rock armour and natural siltation) on the river/sea bed, risking a sunken ship/anchor strike
- Direct contact with water necessitates careful waterproofing design around the joints
- The segmental approach requires careful design of the connections, where longitudinal effects and forces must be transferred across
- Environmental impact of tube and underwater embankment on existing channel/sea bed.

Tubes can be round, oval and rectangular. Larger strait crossings have selected wider rectangular shapes as more cost effective for wider tunnels.

Examples

The first tunnel constructed with this method was the Shirley Gut Siphon, a six foot sewer main laid in Boston, Massachusetts in 1893. The first example built to carry traffic was constructed in 1910 to carry the Michigan Central Railroad under the Detroit River.

Other examples include:

- The Louis-Hippolyte Lafontaine Bridge-Tunnel in Montreal, Canada
- The Drogden Tunnel, part of the Øresund Bridge complex connecting Denmark and Sweden
- Marmaray, Istanbul, Turkey, the world's deepest immersed tunnel
- Hong Kong Cross-Harbour Tunnel
- 63rd Street Tunnel, a four-bore rail tunnel under the East River in New York City
- Sydney Harbour Tunnel - road
- Transbay Tube, a BART subway rail tunnel under San Francisco Bay, California
- Detroit-Windsor Tunnel, two-lane automobile tunnel under the Detroit River, leading from Windsor, Ontario to Detroit, Michigan
- The Posey and Webster Street Tubes, connecting Oakland and Alameda, California

- The Fort McHenry Tunnel and the Baltimore Harbor Tunnel in Baltimore, Maryland
- Jack Lynch Tunnel in Cork, Ireland
- Limerick Tunnel in Limerick, Ireland
- A55 Conwy Bypass Tunnel, Conwy, Wales, United Kingdom
- The Ted Williams Tunnel in Boston, Massachusetts
- The Maastunnel in Rotterdam, Netherlands
- The tunnel sections of the Chesapeake Bay Bridge-Tunnel connecting Virginia Beach and the Eastern Shore of Virginia
- The Medway Tunnel in Kent, United Kingdom
- Tingstadstunneln, Sweden
- New Tyne Crossing, Newcastle, United Kingdom
- The George Massey Tunnel, connecting Delta and Richmond, British Columbia
- The Washington Metro Yellow Line tunnel from South Potomac Park heading into Washington DC just after crossing a bridge over the Potomac River.
- The concrete immersed rectangular tubes Tokyo Port Daiichikoro tunnel (Rinkai Tunnel) built in 2001

Chapter 9

Ley Tunnel

Ley tunnels are a common element of the local folklore tradition in the United Kingdom and they also occur in Europe. In Norwegian a ley tunnel-like passage is called a "lønngang" (lønn = "hidden / secret", and gang = passage) and in Swedish a "lönngång". Ley tunnels are said to physically link together prominent places such as country houses, castles, churches, ancient monuments and other, often medieval, buildings.

Legends about the existence of ley tunnels involve usually improbably long subterranean passages, sometimes running under major obstacles such as rivers and lakes to reach their destinations. Religious buildings, monks and the landed gentry are a particularly common element in many of the ley tunnel stories.

It is unlikely that many of the recorded ley tunnels exist physically, for this is a characteristic of their very nature; their significance lies in why so many similar legends of Ley tunnels have arisen and in their connection with the more esoteric notions of channels or paths of earth energy, etc.

The origins of secret passage myths

One of the entrances to the Cleeves Cove cave system in Scotland; the Elfhame

Inside the main chamber of Halliggye Fogou, Trelowarren, Cornwall

Underground structures have a fascination due to their being hidden from view and their contents, purpose, extent and destinations remaining unknown. Over the centuries many underground structures have been discovered by chance, ranging from Cornish Fogous, souterrains that are possibly Pictish, Roman and medieval sewers to 'smugglers' tunnels', escape tunnels, siege tunnels, and the like.

On occasion possible ley tunnels will prove to be of a purely natural origin, greatly exaggerated, such as at Cleeves Cove cave in Scotland, or Kents Cavern in England. The site at Cleeves Cove cave was previously known as the 'Elfhouse' or 'Elfhame' the locals at that time believing that elves had made it their abode.

Canyon passage in Mammoth Cave, the world's longest cave

Rarely natural caves or tunnel systems can be of great extent; the cave system with the greatest total length of passage is Mammoth Cave (Kentucky, USA) at 591 kilometers (367 mi) in length, whilst the next most extensive known cave is Jewel Cave near Custer, South Dakota, USA, at 225 kilometers (140 mi).

Some castles really did have escape tunnels, such as the short one located at Loudoun Castle in Ayrshire, Scotland, which leads from the old kitchens to a 'tunnel-like' bridge over the Hag Burn. Others examples were longer: at Nottingham Castle, the young king Edward III was imprisoned by Roger de Mortimer, 1st Earl of March. In 1330 a small group of armed supporters of Edward III used a secret passage to attack Mortimer. The attackers entered through a long, winding secret passage which led directly into the castle, allowing them to surprise and capture Mortimer.

The ice house entrance, Eglinton Country Park

Other tunnels are products of an excessive desire for personal privacy, such as at Welbeck Abbey and Brownlow Castle; another ley tunnel type allowed for the supposed free and secret movement of monks, abbots and other ecclesiastics who may have had cause to keep a low profile for fear of attack or abusive treatment during periods of unrest, etc. Smugglers at times avoided the excise man through what are often simply just drains, sewers or water supply conduits. Some genuine smugglers' tunnels do seem to exist however.

Bruce Walker, an expert on Scottish vernacular architecture, has suggested that the relatively numerous and usually long ruined ice houses on country estates have led to Scotland's many legends of ley tunnels. The appearance of ice house entrances lends itself to the unitiated making such deductions, seeing as how ice houses are often found in ha-ha walls, house and stable basements, woodland banks, open fields, etc.

Many legends are associated with the actual and supposed activities of the Knights Templar and this is a rich vein for stories about tunnels connecting together the various properties that the order used to possess up to the 12th century, when they were suppressed.

Sigmund Freud, Jung and others have various psychological interpretations of the symbolic meanings of tunnels and these clearly have a part to play in the origins of ley tunnel myths.

The ley line connection

King's College Chapel seen from Clare College

It has been suggested that an ancient ley line system once existed and was very nearly lost from folk memory, saved through legends of ley tunnels, place names, etc. Ley lines may therefore be perpetuated in the legends and rumours of secret passages or ley tunnels running for considerable and unlikely distances underneath the British countryside between prominent features of the landscape. Alfred Watkins, in *The Old Straight Track*, suggests that they might be connected with leys. Michael Behrend in *The Landscape Geometry of Southern Britain* states that the tunnel in Cambridge linking Kings College Chapel to Granchester Manor is a ley.

An example of a link between ley tunnels and ley lines has been suggested through the writings of the Rev William Beresford, Vicar of St Luke's, Leek, from 1882 to 1919. This keen antiquarian wrote about a "secret route" that went from Dieulacresse abbey in Leek, across Blackshaw Moor and ran towards Thorncliffe; this was not a true tunnel, but it was secret in that the track was sunk below ground level, allowing the monks in this instance to move about more or less hidden from the surrounding area.

Ley tunnel examples

Scotland

Caldwell House circa 1910

Blackness Castle in Lothian is said to have a tunnel linking it with the House of Binns, which lies about three kilometres distant from it. A tunnel is said to run from Stanecastle near Irvine to Eglinton Castle and another from Stanecastle to Seagate Castle in Irvine, complete with a mythical piper. Monkredding was a property of Kilwinning Abbey and a tunnel is said to link the two properties. Another tunnel is said to run from Stanecastle to Dundonald. A subterranean passage was found by workmen at Stanecastle in the 19th century.

Ravenscraig Castle in Scotland

A tunnel is said to run from near Ravenscraig Castle down to the Annick Water just up stream of Lainshaw Castle. The tunnel was crawled through by the grandfather of a local man. This tunnel may be related to the drainage of the nearby, now flooded, Hillhouse quarry, the Water Plantation area and other Lainshaw estate lands.

A tunnel is said to run from Loudoun Castle under the River Irvine to Cessnock Castle in Galston, East Ayrshire, Scotland.

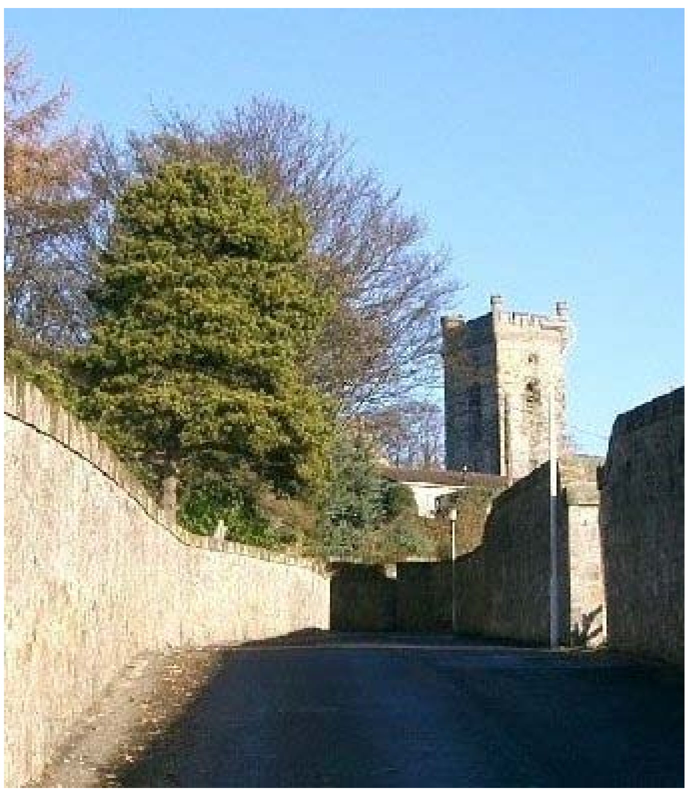
A tunnel is said to run from the old Giffen Castle near Beith to the now abandoned farm of Bank of Giffen; some years back some children are said to have found and made their way safely through the tunnel.

A secret or Ley tunnel is said to link Old Auchans and Dundonald Castle. A local loch was being drained through a ditch when it was observed that the water was vanishing into the earth; locals thought that the ley tunnel had been breached.

Cleeves Cove cave, the site of the Elfhame is said to be connected to Loudoun Hill and once the Laird of Auchenskeichs (sic) Collie dog entered the cave at its entrance above the Dusk Water and came out at Loudoun Hill near Darvel, many miles away. The end of the Cleeve Cove system is said to have never been found. Mauchline Castle is said to be linked to Kingencleugh Castle by a tunnel.

A tunnel is said to run the one and a half miles from Craufurdland Castle to the Dean Castle in Kilmarnock, Ayrshire. It was used to provision the Dean Castle when it was besieged for several months in the time of Edward I and the troops only gave up when the besieged hung several freshly killed sheep over the wall and offered them to the attackers. The tunnel entrance was only blocked up in the early 19th century. Cuthbertson records the tradition of a tunnel running from Dean Castle down to the Kilmarnock Water near the old Begbie's Tavern of Burn's fame. This tunnel is said to have become a public sewer.

A local tradition was that an underground passage ran from Caldwell House to the old Lugton Inn (now demolished), under the Lugton Water. A search by owners in the cellars did not revealed any signs of a hidden passage.



Culross Abbey in Fife

Persistent rumours exist of a tunnel which is said to run from Kilwinning Abbey, under the 'Bean Yaird', below the 'Easter Chaumers' and the 'Leddy firs', and then underneath the River Garnock and on to Eglinton Castle. No evidence exists for it, although it may be related to the underground burial vault of the Montgomeries which does exist under the old abbey or to the main sewer that would have led from the monastery to the river.

In the village of Carmunnock near Glasgow a tunnel is said to have connected the parish church with dwellings used by the monks on what is now Busby Road. No sign of the tunnel has yet been found.

At Strathaven Castle in South Lanarkshire tunnels are recorded in local tradition as running from the castle to the Sweetie's Brae, Mill Brae, and the Tower. Road works in the 19th century did not reveal anything of their existence.

A tunnel is believed to exist beneath Culross Abbey in Fife and within is said to sit a man in a golden chair waiting to give valuable treasures to anyone who succeeds in finding him. Many years ago a blind piper decided to try and upon entering at Newgate with his dog he proceeded to search and could be heard playing his pipes as far as the West Kirk, three quarters of a mile away. Eventually the dog emerged into the daylight, however the piper was never seen, or heard of, again. The caves below Keil Point on Isle of Arran contain a slab which may have been an ancient altar. It has the prints of two right feet on it, said to be of Saint Columba.

In the 19th century some women found the secret tunnel of Coupar Angus Abbey near the entrance to the churchyard. One went in and was never seen again, however in 1982 a local mason found the entrance again and went in some distance before finding a cave in. It is said that the tunnel ran a further two and a half miles to a souterrain at Pitcur. Fingask Castle has underground passages, still partly open in 1766, said to run to Kinnaird Castle, two kilometres away. A ley tunnel is said to run under the Tay between the hospital of Seggieden and the nunnery at Elcho. Newton Castle in Blairgowrie is said to have a tunnel that runs to Ardblair. Ashintully Castle in Strathadle and Glenshee has a tunnel linking it to its predecessor, Whitefield Castle. In the Weem area Saint David's Well is said to have a cave beneath it which connects with another cave at Loch Glassie, two kilometres away. At Monzievaird Castle in Strathearn a secret tunnel is said to run from the castle to the Turret Burn.

Near Moniaive in Dumfries and Galloway a tunnel is said to have run from under the Caitloch bridge over the Dalwhat Water to Caitloch House, some distance away. The tunnel is said to have been used by Covenanters evading the King's Dragoons during those troubled days and is now blocked.

Brodick Castle on the Isle of Arran had a tunnel which apparently ran down to the shore in Brodick Bay. Circa 1920 the duchess was renovating the castle and had a hollow sounding section of wall opened up. This work quickly ceased when a story was remembered of two plague victims in the 18th century having been walled up in an old tunnel, first having been covered in quicklime and rubble.

Gordon in 1726 records that at Ardoch Roman Fort near Dunblane in Perth and Kinross a subterranean passage was said to run from the fort, under the River Tay, to the fort or

'Keir' on Grinnin Hill. This tunnel is said to contain a great deal of treasure as recorded in these lines;

"From the Camp of Ardoch,
To the Grinnin Hill of Keir,
Are nine Kings rents,
For seven hundred year."

England

At Furness Abbey a tunnel has been said to run underneath the Abbey to both Piel Castle and Dalton Castle. This was said to be how the monks travelled to and from each monument to receive foodstuffs and keep watch upon the towns. It has also been rumoured that the Holy Grail and King John’s missing jewels, are actually hidden somewhere inside.

Richmond Castle

Richmond Castle in North Yorkshire standing in an impressive cliff-top position overlooking the River Swale. A potter named Thompson is said to have discovered a tunnel entrance at the bottom of this cliff. Following it deep into the hillside, he came to a large cavern where slept King Arthur and his knights around the famous Round Table. On the table lay an ancient horn and a mighty sword. Thompson reached out and picked up the horn, but the sleepers began to awake and, fearing for his life, the potter fled. As he raced down the tunnel back to daylight and safety, he heard a voice behind him declare:

"Potter Thompson, Potter Thompson!
If thou hadst drawn the sword or blown the horn,
Thou hadst been the luckiest man e'er was born."

The tunnel appears to have been well known, though the cave remains hidden. A second story tells how this subterranean passage is supposed to run from the Castle to nearby Easby Abbey. Some soldiers once sent a drummer-boy along it to test the theory and followed the sound of his drum almost halfway to the Abbey. Then the drumming stopped! The boy was never seen alive again - but his ghost is said to haunt the tunnel from where a slow drumbeat is still sometimes heard. A memorial stone marks the spot at which the drum beat was last heard. It is believed that the legendary tunnel was constructed in medieval times as an escape route to the castle for the Abbot and Canons of the Abbey in case of an attack from the Scots, who were continually making raids into the northern counties of England.

Hertford Castle

A smugglers' tunnel is said to run from Smugglers' Farm in Herstmonceux, Sussex to the Pevensey Marshes, a good distance away. A whole network of secret Knights Templar tunnels are said to run beneath Hertford Castle, running to Dinsley and other local places.

A 'secret tunnel' exists at Pevensey Castle in East Sussex, although not open for public access - it links the keep with the former market square and is thought to be Norman in origin, although was reused during WWII.

Glastonbury Tor

A series of tunnels are said to lie beneath Glastonbury Tor. The most famous tale is about a tunnel from Glastonbury Abbey to the Tor. At one time some thirty monks are rumoured to have entered the Tor via this tunnel, but only three came out again, two insane and one struck dumb. Another legend which is widely believed is that of the long-distance tunnel leading from the crypt of the Lady (or Galilee) Chapel, under the River Brue to a distant point, possibly to the village of Street, where a passage exists from an outlying building in the grounds of the old manor house. A dog is said to have been put into the tunnel at Street and found his way out at the Glastonbury end.

A tunnel is said to run from King's College Chapel to Granchester Manor, Cambridge, passing under the river Cam.

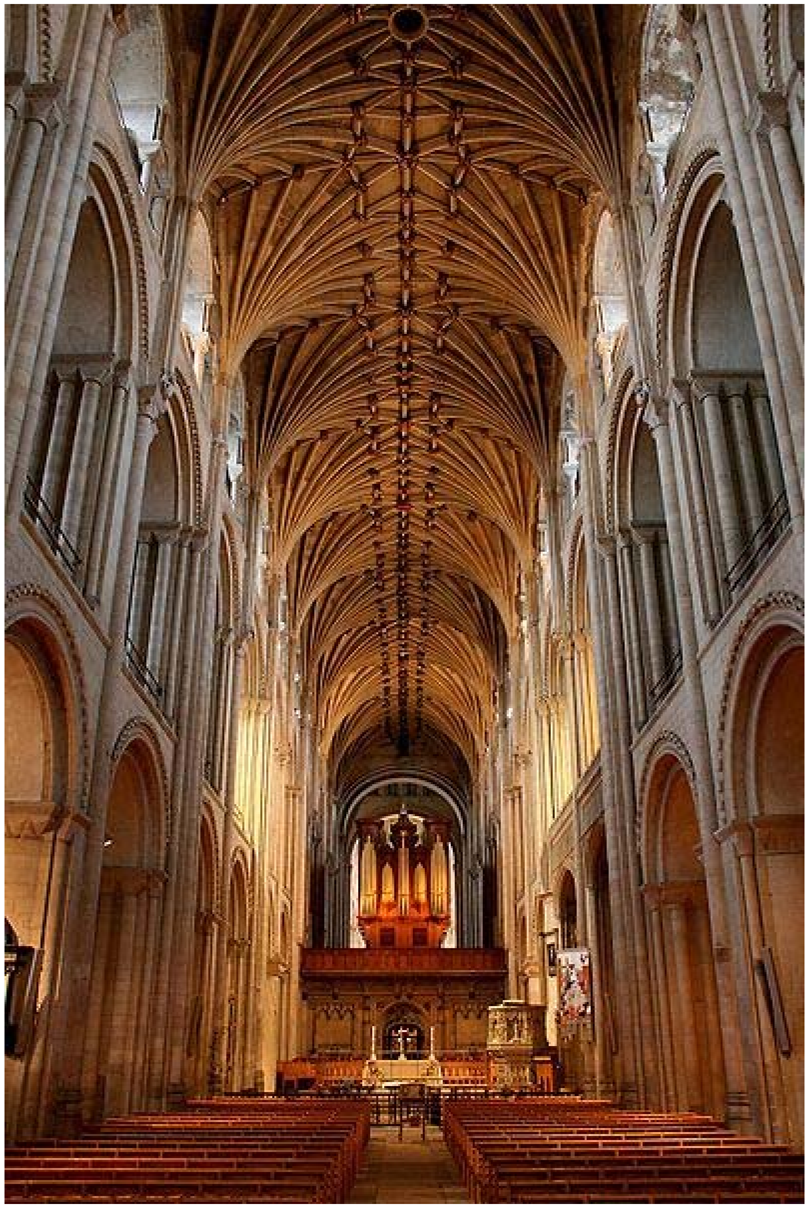
Evidence of tunnels have recently been found beneath Saint Luke's, Leek's old church, reinforcing legends of a ley tunnel running from the church to Dieulacresse abbey.

A tunnel is said to run from Newbury Town Hall to St Nicolas Church. This belief may have started because there are east west flowing brick victorian service tunnels running from roughly the Newbury arcade towards this church; these were exposed to the public's gaze during construction work. A tunnel is also said to run from Newbury Castle (400 ft above sea level) and Shaw House (260 ft, thus 140 ft below it). The point of entry is said to be hollow space (now blocked) in the south-east angle of the enclosure. In 1930 workmen investigated the legend by excavations of the entrance, but found nothing.

At Necton in East Anglia a tunnel is said to run from the restored 14th century church of All Saints to Necton Hall, in possession of the Mason family since the time of Henry VII.

Gisborough Priory

The first of a number of legendary tunnels under Norwich leads from the Castle (TM232085) to the Guildhall (TM231085) near the market-place, erected 1407 - 13 on the site of the old tollhouse. It still has a 14th century vault below it, that was the crypt (and prison) of the former building. A second tunnel (in which a pig was once lost) heads from the Castle for Carrow Priory (TM242073 area), a Benedictine nunnery whose scant 12th century remains on the outskirts of Norwich are incorporated into a residence of the Colman family, near the junction of King Street and Bracondale. The third tunnel from the Castle ran to the Norman cathedral to the north-east (TM235089), begun in 1096 by Bishop Herbert de Losinga, and finally consecrated in 1101 - 2. Yet another subterranean way links the Castle with the Crown Derby near the Guildhall.



The interior of Norwich Cathedral - the Nave

At Norwich Cathedral another tunnel begins, running for about nine miles to the ruins of St. Benet's Abbey (TG383157) on the marshes at Ludham. A much shorter one, allegedly used by monks, was said to run from the cathedral to Samson & Hercules House. The Anglia Restaurant in Prince's Street has a splendid groined crypt for a cellar, and two tunnels from here are said to lead to the cathedral, and to St. Andrew's Hall. Monks supposedly used a tunnel from the cellars of the Shrub House at the corner of Charing Cross Street, to the site of St. Benedict's Gates.

In early January 1644, Cromwell sent his forces to Norwich to demand the surrender of a small group of Royalists, whom he heard to be presently at the Maid's Head Hotel. According to legend, as the Parliamentarians entered the hotel, the Royalists retreated through a secret tunnel, stretching steel ropes across the way behind them. Many of Cromwell's men (and their horses) were beheaded as they raced through the tunnel in pursuit, and this incident is used to explain the sound of ghostly hoofbeats often heard emanating from under the ground around the Cathedral Close.

One smugglers' tunnel was rumoured to run from Kinson, now a Bournemouth suburb, to the coast some four miles away.

In the 19th century, it was said that an underground passage ran from the remains of the 12th century Gisborough Priory, immediately south of Guisborough parish church, to a field that lay in the parish of Tocketts. Halfway along was said to be a chest of gold guarded by a raven or crow. In Cleveland almost every old castle and ruined monastery has its legend of a subterranean passage leading therefrom, which someone has penetrated to a certain distance, and has seen an iron chest, supposed to be full of gold, on which was perched a raven. The raven may suggest a Scandinavian origin of the legends.

Binham Priory

Bracknell's Old Manor is a beautiful 17th century brick manor house complete with priest hole. It is said to have secret passages connecting to various locations.

Droitwich Spa is said to have a passageway that leads from St Augustine’s church, Dodderhill, to Friar Street in the town centre. A system of tunnels is said to run from there to St Augustine’s and St Andrew’s churches.

The story that Thomas a Becket from Northampton Castle is a well documented part of 12th century history but how the persecuted Archbishop of Canterbury managed to flee from the fortress remains a mystery. One myth is that he fled from the clutches of Henry II through a tunnel that linked the castle to All Saints Church in Mercers Row.

At Binham Priory in Norfolk a fiddler entered the tunnel which ran beneath the building and could be heard for some distance before suddenly ceasing. The fiddler was never seen again.

The rhyme below dates from the 17th century and recalls the tradition that a tunnel connects what is now Syon House with the friary of Sheen at Richmond in Surrey, a considerable distance away.

> *"The Nun of Sion, with the Friar of Shean,*
> *Went under water to play the Quean."*

The origin of the legend remains a mystery.

In Leicestershire a subterranean passage is said to connect a nunnery which once stood near the Humber Stone with Leicester Abbey. In the cellars under Leicester Castle a witch known as 'Black' or 'Cat Anna' is said to have lived. She is said to have journeyed to the Dane Hills through an underground passage.

Wales

Local legend states that a tunnel connects the now ruined Court Farm with the nearby church in Pembrey, South Wales.

Ireland

In Lurgan a tunnel supposedly went from Brownlow House to the local police station, the courthouse and to the church in the middle of the town. Another tunnel was from Soyes Mill to Lurgan Castle. One explanantion for the Brownlow tunnel was that Lord Brownlow had a very over protective wife, and after many years of a good marriage, things went sour, so Brownlow had this Tunnel dug so he would be able to exit the castle after dark without his wife finding out. Once out, he would go on the hunt for some Lurgan lassies, Book a room at the Ashburn Hotel, then leave early in the morning to get back in time for breakfast at the castle with the wife. Lakafinna, to the South of Bullaun, has a castle and local folklore relates that a tunnel exists between this castle and the village of Ballyara.

Denmark

Aalborghus castle

In the city of Aalborg a tunnel is said to have run from the convent under the fjord to another convent near Sundby. This tunnel had branches which ran to an old bridge, two churches and to the castle of Aalborghus. A student once tried to explore the tunnels with a long cord, a sword and a light. The broken cord was retrieved, but the student was never seen again.

Ukraine

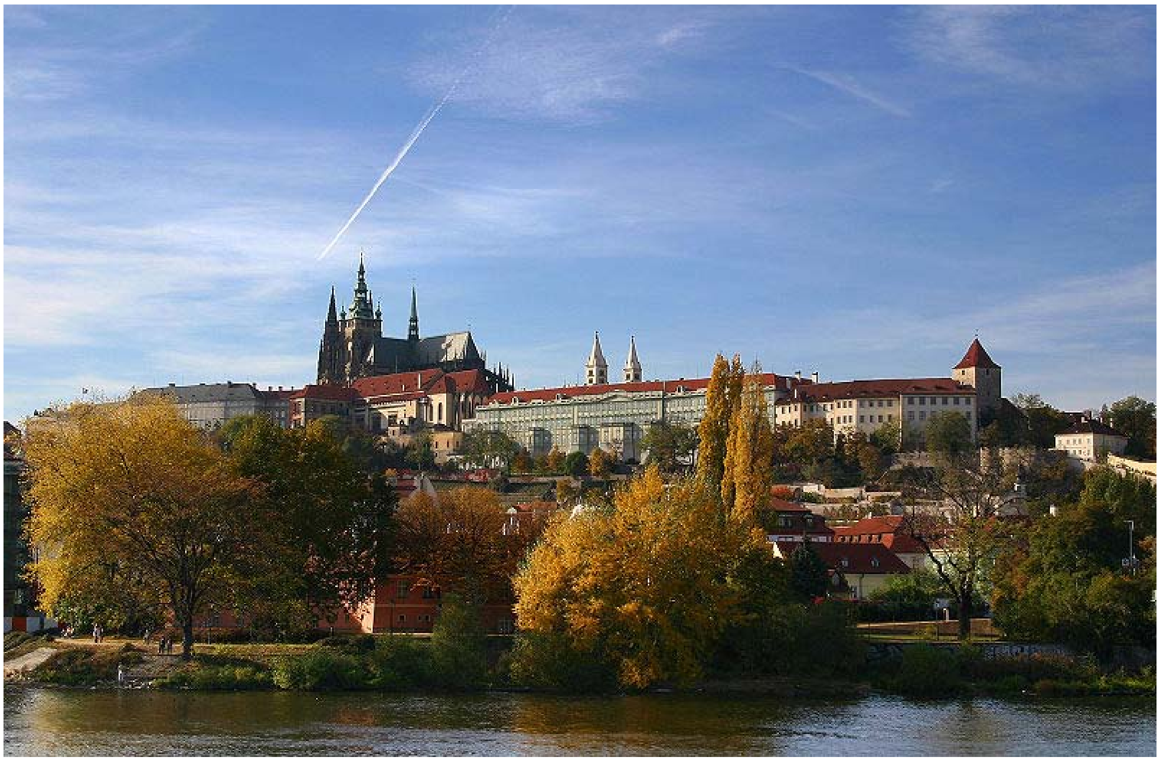
A mysterious tunnel is said to run to Kniazh Hill that was used during emergencies by the Semashko Princes and the other owners of Gubkiv Castle, the powerful princes Danylovych. This tunnel, it is said, starts near the deep well in the castle yard.

Subterranean passages

Ley tunnels differ from most of the numerous examples of actual secret passages and the like in that Ley tunnels are usually very long. Many examples of extensive underground passages do actually exist, built for a variety of purposes, however they often lack the link with churches, aristocracy, etc and do not necessarily involve prominent buildings.

An exception is the Ley tunnel that is said to run from the 'bottomless' Saint Michael's Cave in Gibraltar under the Strait of Gibraltar, exiting in Morocco, Africa.

Drains, sewers and water supplies



Prague Castle

Drains, sewers and water supply tunnels often have a more than superficial resemblance to pedestrian tunnels and have added to legends of mysterious passages of a secretive and ambiguous purposes.

An example of a medieval building with many subterranean passages is Prague Castle. In the Middle Ages underground passages were dug out mainly for purposes of defence and later drainage conduits sufficed to take the waste waters to the foot of the castle wall and then let it fall freely over the slope of the bare cliff face into the bed of the Brusnice stream. The inhabitants of the Castle complained of the smell of the slope, so two conduits were built as far as the Brusnice stream. One leads from Hradcany Square and the other, known as the castle passage, from the second Castle courtyard to the bottom of the Deer Moat.

At Paisley Abbey in Scotland, few of the original monastic buildings survived into the 20th century, so landscaping of the area around the church in 1990 provided the ideal opportunity to investigate the positions of those now "lost". The main drain, which would have brought fresh water into the complex, and taken away the effluents, would have acted as the spinal column of the buildings. Local knowledge led to the rediscovery of a substantial medieval drain with fine stonework and enough space for a person to walk through.

In Exeter, South Devon, medieval tunnels dating from the 14th century under the High Street are a unique ancient monument. The tunnels were built to house the pipes that brought fresh water to the city. These Underground Passages have long exercised a fascination over local people, bringing stories of buried treasure, secret escape routes, passages for nuns and priests - even a ghost on a bicycle. Their purpose was simple: to bring clean drinking water from natural springs in fields lying outside the walled city, through lead pipes into the heart of the city.

Siege mines or tunnels

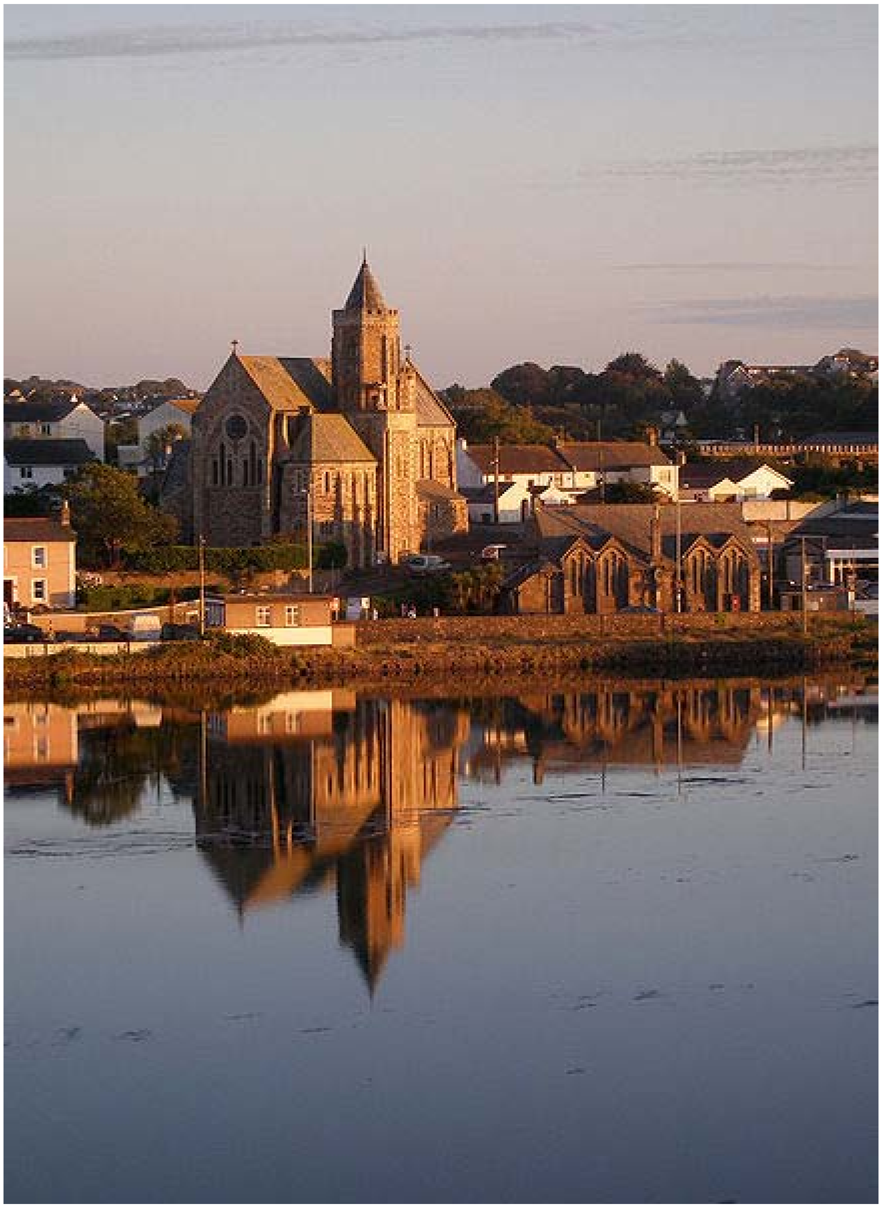
Saint Andrews castle ruins

Such tunnels may have led to the creation and survival of local legends of subterranean passages. An example of a well documented tunnels is the one dug at St Andrews in Scotland. Cardinal Beaton in March 1546, had the Protestant preacher, George Wishart, burnt at the stake in front of his castle walls and this was subsequently used as a pretext for Beaton's murder at the hands of local Protestant lairds who captured the castle by stealth. A long siege followed on the orders of the Regent, the Earl of Arran, however by November 1546 this had resulted in a stalemate. A determined effort to undermine the walls of the castle via a spacious tunnel large enough to take pack animals was intercepted, after several false starts, by the defenders. They dug a low, narrow and twisting countermine through the rock that eventually broke into the mine itself.

Escape tunnels

Many medieval buildings are said to have had escape tunnels, secret by nature and hence likely to be the stuff of myth, legend and exaggeration. One example is the escape tunnel running from Maynooth Castle has its exit at the tower in Laraghbryan. A short escape tunnel has been located at Loudoun Castle in Ayrshire, Scotland, which leads from the old kitchens to a 'tunnel-like' bridge over a burn. Other escape tunnels were longer, such as at Nottingham Castle, where the young king Edward III was imprisoned by Roger de Mortimer, 1st Earl of March. In 1330 a small group of armed supporters of Edward III used a secret passage to attack Mortimer. The attackers entered through a long, winding secret passage which led directly into the castle, allowing them to surprise and capture Mortimer, releasing the king who was unharmed.

Smugglers' tunnels



The Copperhouse Pool, Hayle

Porthcothan Bay

Virtually every village close or on the Southern coast of England has a local legend of a smugglers' tunnel; the entrances to most of the actual smuggler's tunnels have been lost or bricked up.

Some tunnel stories turn out to be very plausible, such as the tunnel at Hayle in Cornwall which really does seem to have been built specifically for smuggling. In other instances the tunnel either doubles as a storm drain or some other functional channel, or else is an extension of a natural fissure in the rock, as at Methleigh and Porthcothan respectively.

Chapter 10

Tunnelling Shield & Shotcrete

Tunnelling Shield

Photo of the tunnelling shield used for the construction of the Xinyi Line on the Taipei Metro system in Taiwan.

A **tunnelling shield** is a protective structure used in the excavation of tunnels through soil that is too soft or fluid to remain stable during the time it takes to line the tunnel with a support structure of concrete, cast iron or steel. In effect, the shield serves as a temporary support structure for the tunnel while it is being excavated.

History

The first successful tunnelling shield was developed by Sir Marc Isambard Brunel, and patented by him and Lord Thomas Cochrane in January 1818. Brunel and his son Isambard Kingdom Brunel used it to excavate the Thames Tunnel, beginning in 1825 (though the tunnel would not be opened until 1843). Brunel is said to have been inspired in his design by the shell of the shipworm *Teredo navalis*, a mollusc whose efficiency at boring through submerged timber he observed while working in a shipyard. The shield was built by Maudslay, Sons & Field, of Lambeth, London, who also built the steam pumps for de-watering the tunnel.

Brunel's original design was substantially improved by Peter W. Barlow in the course of the construction of the Tower Subway under the River Thames in central London in 1870. Probably the most crucial innovation of Barlow's design was that it had a circular cross-section (unlike Brunel's, which was of rectangular cross-section), which at once made it simpler in construction and better able to support the weight of the surrounding soil.

The Barlow design was enlarged and further improved by James Henry Greathead for the construction of the City & South London Railway (today part of London Underground's Northern Line) in 1884. To this day, most tunnelling shields are still loosely based on the Greathead shield.

Manual shield tunneling

In early shield tunneling, the shield functioned as a way to protect labourers who performed the digging, and moved the shield forward, progressively replacing it with pre-built sections of tunnel wall. The early deep tunnels for the London Underground were built in this way. The shield divided the workface into overlapping portions that each worker could excavate.

Modern tunnel boring machines

A tunnel boring machine (TBM), consists of a shield (a large metal cylinder) and trailing support mechanisms.

At the front end of the shield a rotating cutting wheel is located. Behind the cutting wheel there is a chamber where, depending on the type of the TBM, the excavated soil is either mixed with slurry (so-called slurry TBM) or left as-is (earth pressure balance or EPB shield). The choice for a certain type of TBM depends on the soil conditions. Systems for removal of the soil (or the soil mixed with slurry) are also present.

Behind the chamber there is a set of hydraulic jacks supported by the finished part of the tunnel which are used to push the TBM forward. Once a certain distance has been excavated (roughly 1.5-2 meters), a new tunnel ring is built using the erector. The erector is a rotating system which picks up precast concrete segments and places them in the desired position.

Behind the shield, inside the finished part of the tunnel, several support mechanisms which are part of the TBM can be found: dirt removal, slurry pipelines if applicable, control rooms, rails for transport of the precast segments, etc.

Lining

The tunnel lining is the wall of the tunnel. It usually consists of precast concrete segments which form rings. Cast iron linings were traditionally used in the London Underground tunnels, while steel liners were sometimes used elsewhere.

Shields in Japan

In Japan there are several innovative approaches to shield tunneling, e.g. the Double-O-Tube or DOT-tunnel. This tunnel looks like two overlapping circles. There are also shields with computerized arms which can be used to dig a tunnel in virtually any shape.

Shotcrete

Shotcrete nozzle with 75 mm concrete hose from line pump and 20 mm compressed air line.

Shotcrete swimming pool under construction in Northern Australia.

Shotcrete is concrete (or sometimes mortar) conveyed through a hose and pneumatically projected at high velocity onto a surface, as a construction technique.

Shotcrete is usually an all-inclusive term; **gunite** is a term sometimes used for some dry-mix types.

Shotcrete undergoes placement and compaction at the same time due to the force with which it is projected from the nozzle. It can be impacted onto any type or shape of surface, including vertical or overhead areas.

History

Shotcrete was invented in the early 1900s by American taxidermist Carl Akeley, used to fill plaster model of animals. He used the method of blowing dry material out of a hose with compressed air, wetting it as it was released. This was later used to patch weak parts in old buildings. In 1911, he was granted a patent for his inventions, the "cement gun", the equipment used, and "gunite", the material that was produced. Until the 1950s when the wet-mix process was devised, only the dry-mix process was used. In the 1960s, the alternative method for gunning by the dry method was devised with the development of the rotary gun, with an open hopper that could be fed continuously. Shotcrete is also a viable means and method for placing structural concrete.

The nozzleman is the person controlling the nozzle that delivers the concrete to the surface. The nozzle is controlled by hand on small jobs, for example the construction of small swimming pools. On larger work the nozzle is held by mechanical arms and the nozzleman controls the operation by a hand-held remote control.

Dry mix vs. wet mix

The dry mix method involves placing the dry ingredients into a hopper and then conveying them pneumatically through a hose to the nozzle. The nozzleman controls the addition of water at the nozzle. The water and the dry mixture is not completely mixed, but is completed as the mixture hits the receiving surface. This requires a skilled nozzleman, especially in the case of thick or heavily reinforced sections. Advantages of the dry mix process are that the water content can be adjusted instantaneously by the nozzleman, allowing more effective placement in overhead and vertical applications without using accelerators. The dry mix process is useful in repair applications when it is necessary to stop frequently, as the dry material is easily discharged from the hose.

Wet-mix shotcrete involves pumping of a previously prepared concrete, typically ready-mixed concrete, to the nozzle. Compressed air is introduced at the nozzle to impel the mixture onto the receiving surface. The wet-gun procedure generally produces less rebound, waste (when material falls to the floor), and dust compared to the dry-mix procedure. The greatest advantage of the wet-mix process is that larger volumes can be placed in less time.

Shotcrete vs. gunite

Shotcrete is today an all-inclusive term that describes spraying concrete or mortar with either a dry or wet mix process. However, it may also sometimes be used to distinguish from gunite as a wet-mix. The term shotcrete was first defined by the American Railway Engineers Association (AREA) in the early 1930s. By 1951, shotcrete had become the official generic name of the sprayed concrete process.

Gunite refers only to the dry-mix process, in which the dry cementitious mixture is blown through a hose to the nozzle, where water is injected immediately before application. Gunite was the original term coined by Akeley, trademarked in 1909 and patented in North Carolina. The concrete is blasted by pneumatic pressure from a gun, hence "gun"-ite.

The term "Gunite" became the registered trademark of Allentown, the oldest manufacturer of gunite equipment. Other manufacturers were thus compelled to use other terminology to describe the process such as shotcrete, pneumatic concrete, guncrete, etc. Shotcrete emerged as the most commonly used term other than gunite, and after the later development of the wet process came to be used for both methods.

Reinforcement

A 76 mm borehole in fibre reinforced shotcrete on a tunnel wall

Sprayed concrete is reinforced by conventional steel rods, steel mesh, and/or fibers. Fiber reinforcement (steel or synthetic) is also used for stabilization in applications such as slopes or tunneling.

Shotcrete-stabilized cliff above a motorway in New Zealand

Chapter 11

Spiral Tunnels and Tunnels on a Curved Alignment

Lists of spiral (helicoidal) tunnels and tunnels on a curved alignment on railway lines worldwide.

A part of a line is bracketed (), if it is located in a country other than that mentioned in the specific table:

Example: :(Lausanne – Montreux – Sierre – Visp – Brig –) -> Switzerland

Africa

South Africa

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
	Van Reenen		Spiral				1,067	South African Railways	28°22′01″S 29°25′50″E / 28.367°S 29.43049°E

Americas

United States

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks

	Stevens Pass	Martin Creek	Spiral	about 1000 feet	2.2		standard - 4' 8 1/2"	Great Northern Railway	Built by 1883, Retired in 1929 by the opening of the new Cascade Tunnel. 47°43′26″N 121°12′01″W / 47.723822°N 121.200340°W

Canada

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
	Kicking Horse Pass	Big Hill	Spiral	two of 900	22	Adhesion	1,435	Canadian Pacific	

Europe

Croatia

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
Zagreb - Rijeka	Rijeka	Brajdica	Spiral	1,873	21	Adhesion	1,435	HŽ	Nearly a 360° loop entirely in tunnel.

Germany

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
Offenburg - Singen		Niederwasser Tunnel	Curved alignment	558	17-19	Adhesion	1,435	DB	
Offenburg - Singen	Triberg	Grosser Triberg Tunnel	Curved alignment	835	17-19	Adhesion	1,435	DB	
Wutach Valley Railway		Grosser Stockhalde Tunnel	Spiral	1,700		Adhesion	1,435	DB	
Wutach Valley Railway		Kehrtunnel im Weiler	Curved alignment	1,205		Adhesion	1,435	DB	

Italy

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
(Lausanne – Montreux – Sierre – Visp – Brig –) Iselle – Domodossola	Iselle, Varzo	Varzo	Spiral	2,968	22	Adhesion	1,435	SBB	Simplon Line (probably the longest curved alignment tunnel in the world)
(Locarno – Intragna –) Camedo – Domodossola	Trontano	Pelcetino	Loop/Curved alignment	196	60	Adhesion	1,000	(FART), SSIF	
(Metropolitana di Napoli) Line 1	Napoli		Spiral		55	Adhesion	1,435	Metronapoli	metro/subway line
Ferrovia Nulvi-Tempio-Palau (Italian)	Nulvi – Tempio – Palau (Sardinia)	Galleria elicoidale di Bortigiadas	Curved alignment			Adhesion	950	Trenino Verde	Tourist service only
Torino - San Giuseppe di Cairo - Savona	Savona	Santuario	Curved alignment	2063	30~	Adhesion	1,435	FS	makes a complete loop with some open air sections and other two shorter tunnels
Cuneo - Breil-sur-Roya (France) - Ventimiglia/Nice	Cuneo - Breil-sur-Roya	Unknown	Spiral/Curved alignment			Adhesion	1,435	FS	Four separate spirals plus several further curved alignments. Originally 3-phase electrified.
Roccasecca - Avezzano	Capistrello	Capistrello-La Giorgia	S-shaped	2750	?	Adhesion	1,435	FS	

Switzerland

The turn tunnels in the following table are sorted from West to East according the location of the start point of the line.

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
Bex – Bretaye	Fontannaz-Seulaz	Fontannaz-Seulaz	Loop/Curved alignment	182	195	Rack	1,000	TPC (BVB)	
Martigny – Châtelard(– Vallorcine – Chamonix)	Salvan	Charbons	Loop/Curved alignment	419	200	Rack	1,000	MC	
Zermatt –	Riffelal	Landtunnel	Loop/Curved	174	200	Rack	1,000	GGB	

Gornergrat	p		alignment						
Montreux – Zweisimmen	Montreux	Montreux	Loop/Curved alignment	184	65	Adhesion	1,000	MOB	
Montreux – Zweisimmen	Chamby	Chamby	Loop/Curved alignment	314	67	Adhesion	1,000	MOB	
Aigle – Leysin-Grand Hotel	Leysin-Feydey	Leysin	Loop/Curved alignment	233	223	Rack	1,000	TPC (AL)	
Aigle – Les Diablerets	Aigle	Grand-Hôtel	Loop/Curved alignment	119	60	Adhesion	1,000	TPC (ASD)	
Montreux – Rochers de Naye	Glion	Valmont	Loop/Curved alignment	385	130	Rack	800	MVR (MTGN)	
Montreux – Rochers de Naye	Caux	Tremblex	Loop/Curved alignment	144	220	Rack	800	MVR (MTGN)	
Montreux – Rochers de Naye	Dent de Jaman	Jaman	Loop/Curved alignment	77	220	Rack	800	MVR (MTGN)	
Vevey – Les Pléiades	Vevey	Gilamont	Loop/Curved alignment	84	50	Adhesion	1,000	MVR (CEV)	
Brig – Spiez	Kandergrund	–	Loop/Curved alignment	1,655	27	Adhesion	1,435	BLS	Lötschbergbahn
Zermatt – Visp – Brig – Andermatt – Disentis	Grengiols	Grengiols I	Spiral	502	96	Rack	1,000	MGB	Glacier-Express
Zermatt – Visp – Brig – Andermatt – Disentis	Andermatt	Butzen	Loop/Curved alignment	169	110	Rack	1,000	MGB	Glacier-Express
Zermatt – Visp – Brig – Andermatt – Disentis	Andermatt	Biel	Loop/Curved alignment	279	110	Rack	1,000	Matterhorn-Gotthard-Bahn	Glacier-Express
Zermatt – Visp – Brig – Andermatt – Disentis	Andermatt	Rufenen	Loop/Curved alignment	255	110	Rack	1,000	Matterhorn-Gotthard-Bahn	Glacier-Express
Kleine Scheidegg – Jungfraujoch	Eiger, Mönch	Jungfrau	Loop/Curved alignment	7,122	250	Rack	1,000	JB	The curved alignment is only part of the tunnel.
Grindelwald – Kleine Scheidegg – Lauterbrunnen	Wengen	–	Loop/Curved alignment	248	180	Rack	800	WAB	
Wilderswil – Schynige Platte		Rotenegg	Loop/Curved alignment	168	250	Rack	800	SPB	
Brienz – Rothorn Kulm	Planalp	Schonegg II	Loop/Curved alignment	119	250	Rack	800	BRB	
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Gurtnellen	Pfaffensprung	Spiral	1,476	26	Adhesion	1,435	SBB	Gotthardbahn
Luzern – Göschenen – Airolo – Bellinzona –	Wassen	Wattingen	Loop/Curved alignment	1,084	26	Adhesion	1’435	SBB	Gotthardbahn

Chiasso									
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Wassen	Leggistein	Loop/Curved alignment	1,090	26	Adhesion	1,435	SBB	Gotthardbahn
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Prato	Freggio	Spiral	1,568	27	Adhesion	1,435	SBB	Gotthardbahn
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Prato	Prato	Spiral	1'560	28	Adhesion	1,435	SBB	Gotthardbahn
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Giornico	Pianotondo	Spiral	1,508	26	Adhesion	1,435	SBB	Gotthardbahn
Luzern – Göschenen – Airolo – Bellinzona – Chiasso	Giornico	Travi	Spiral	1,547	27	Adhesion	1,435	SBB	Gotthardbahn
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Filisur	Greifenstein	Spiral	698	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Bergün	God	Loop/Curved alignment	486	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Bergün	Platz	Loop/Curved alignment	262	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Preda	Rugnux	Spiral	662	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Preda	Toua	Spiral	677	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
Chur – Thusis – Tiefencastel – Filisur – Samedan – St. Moritz	Preda	Zuondra	Spiral	535	35	Adhesion	1,000	RhB	Albula Railway Glacier-Express
St. Moritz – Pontresina – Poschiavo(– Tirano)	Alp Grüm	Palü	Loop/Curved alignment	254	70	Adhesion	1,000	RhB	Bernina Railway Bernina-Express
St. Moritz – Pontresina – Poschiavo(– Tirano)	Alp Grüm	Val Pila	Loop/Curved alignment	227	70	Adhesion	1,000	RhB	Bernina Railway Bernina-Express

St. Moritz – Pontresina – Poschiavo(– Tirano)	Poschia vo	Val Varuna I (Oberer Varuna)	Loop/Curved alignment	149	70	Adhesio n	1,000	RhB	Bernina Railway Bernina-Express
St. Moritz – Pontresina – Poschiavo(– Tirano)	Poschia vo	Val Varuna I (Unterer Varuna)	Loop/Curved alignment	147	70	Adhesio n	1,000	RhB	Bernina Railway Bernina-Express
St. Moritz – Pontresina – Poschiavo(– Tirano)	Poschia vo	Balbalera	Loop/Curved alignment	122	70	Adhesio n	1,000	RhB	Bernina Railway Bernina-Express
Landquart – Klosters – Davos	Klosters	Klosters	Loop/Curved alignment	399	45	Adhesio n	1,000	RhB	Replaced 1930 the zig zag in Klosters.
Landquart – Klosters – Davos	Klosters	Cavadürli	Loop/Curved alignment	334	45	Adhesio n	1,000	RhB	
Klosters - Sagliains	Klosters	Zugwald	Loop/Curved alignment	2172	~40	Adhesio n	1,000	RhB	On the ramp to the Vereina Tunnel.

Slovakia

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
Margecany – Červená Skala	Telgárt	Tunnel Telgárt	Curved alignment	1,240	12.5	Adhesion	1,435	ZSSK	

Oceania

New Zealand

Line	Location	Tunnel Name	Kind of Tunnel	Length in m	Gradient in ‰	Kind of Operation	Gauge in mm	Railway Company	Remarks
North Island Main Trunk	Raurimu	Raurimu Spiral	Spiral	383	19	Adhesion	1,067	New Zealand Railways Corporation	