Tunnel engineering

Tunnelling was one of earliest exercises in the field of civil engineering. The ancient Egyptians built tunnels for transporting water and for use as tombs. They also undertook mining operations, cutting deep tunnels to extract copper ore. Today, tunnels are used for road, rail and pedestrian transport, for carrying water, and in mining operations.

Early tunnels

The first underwater tunnel was built in 2160 BC by the engineers of Queen Semiramis of Babylon. The Euphrates river was diverted and the engineers dug a channel in the river bed. In this they built a brick-lined tunnel 900m long, water-proofed with bitumen plaster 2m thick. It provided a walkway connecting the palace with a temple on the other side of the river.

Tunnels have often been used in warfare to penetrate enemy defences. Historians suggest that the walls of Jericho were brought down by driving a tunnel beneath them and then lighting a fire to burn away the wooden props supporting the roof. Tunnel building was an extremely hazardous endeavour in ancient times. Thousands of tunnellers were killed in cave-ins and other accidents.

Tunnels, some cut through hard rock, were used extensively by the Romans in building their aqueducts. The Appian aqueduct, built in about 312 BC, had a tunnel section some 25km long. After the fall of the Roman Empire, no large tunnels were built for 1,000 years. It was the advent of the canal age in the seventeenth century that produced a new generation of tunnel builders.

The first great tunnel built for transportation was part of the Canal du Midi. Completed in 1681, it stretched across France from the Bay of Biscay to the Mediterranean. At Malpus, near Beziers, a 158m tunnel was cut to carry the canal through a rocky ridge. It was the first tunnel built with the aid of explosives.

Rail and underwater tunnels

Throughout the eighteenth century, canal tunnels were built both in Europe and North America. With the onset of the railway age, canals became uneconomic as a means of transport. The construction of railways, however, itself produced a huge increase in tunnelling. One of the most remarkable tunnels was the Simplon tunnel under the Alps, completed in 1906. It runs for 20km and connects Switzerland and Italy, with a 2.1km stretch below Monte Leone cut through solid rock. Another major project was the Seikan Tunnel built to carry high speed trains between the Japanese islands of Honshu and Hokkaido [7]. Construction started in 1972, and tunnelling was completed in 1985. The tunnel runs for 53.8km in the sea bed of the Tsugaru Channel.

Between 1825 and 1842, the French-born engineer Marc Brunel (1769-1849) built the first major underwater tunnel beneath the Thames at Rotherhithe. It is still used today by the London underground railway. His son, Isambard Kingdom Brunel (1806-59), acted as resident engineer on the project. The Brunels constructed the tunnel using a tunnelling shield [1]. This device consisted of a vertical face made from stout horizontal timber baulks, supported by 12 vertical cast iron sections. The baulks were removed one at a time as the engineers removed the clay.

CONNECTIONS

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Traffic engineering
The Channel Tunnel
Railway transport
Railways of the future

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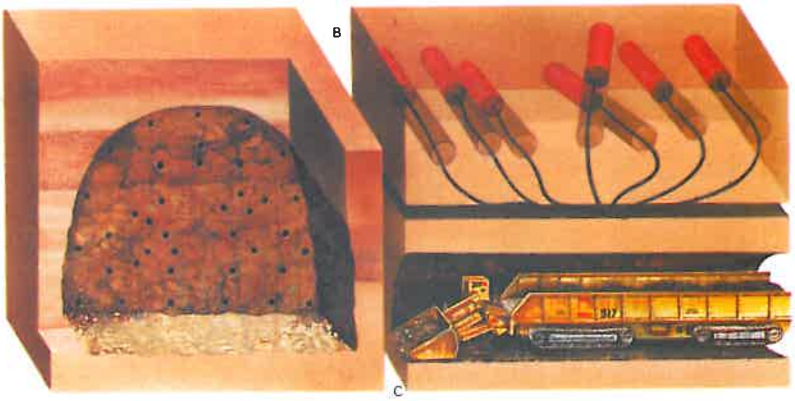
Machines for lifting (6)
Earth moving machines (6)

1

1 Brunel's tunnelling shield consisted of 12 vertical cast-iron sections. Horizontal timbers were positioned across the tunnel face to protect the workers. These were removed one at a time and re-positioned further on as the digging progressed. When the face had been dug about 30cm, the jacks supporting the timbers were released. Larger jacks, acting against the tunnel shields, were then used to move the shield forwards.

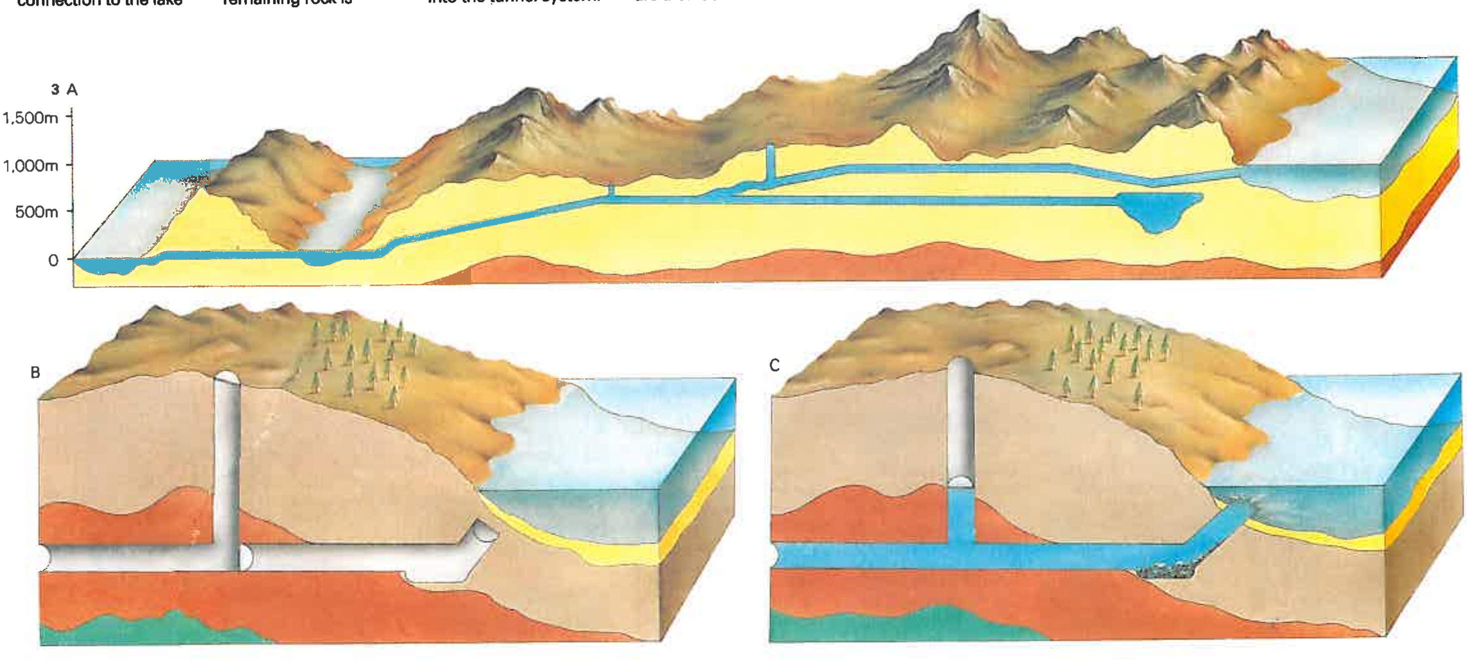
2 A



2 A typical drilling pattern for blasting holes in rock comprises a centre group and one or more outer rings. The holes are packed with a high explosive such as dynamite. The sticks are then detonated in sequence from the centre outwards. [A] shows the holes in a vertical cross-section. A horizontal section [B] shows the dynamite lodged in the rock face. After the explosive has been detonated, a pile of rubble is left blocking the tunnel face. The pattern of holes ensures that the rock is broken up into manageable lumps. A mechanised rock shovel [C] is positioned near the tunnel face for collecting the rubble. The rocks are loaded by the shovel into a long shuttle car and conveyed along a steel-slat conveyor to the awaiting trucks. As the clearing proceeds the machine is able to move closer to the rock face.

3 Water from lakes high in the mountains is tapped to provide hydroelectric power. The water runs through a series of tunnels down to turbo-generators positioned at a lower level [A]. The connection to the lake has to be made well below the water level [B]. This is achieved by digging out a supply tunnel under the lake. The tunnel runs up through stable rock to within a few metres of the bottom. The remaining rock is carefully drilled to take explosive charges, and all the equipment is then removed from the tunnels. Finally, the charges are detonated to shatter the plug [C], allowing the water from the lake to flow into the tunnel system.

3 A



Brunel's shield was the predecessor of the modern circular tunnelling shield.

Some modern tunnels are used to supply water to large urban areas. The longest tunnel in the world is the Delaware aqueduct, supplying water to New York City, and runs for 170km. Others are used as part of hydro-electric power schemes [3].

Modern tunnelling methods

Tunnels through hard rock are usually constructed by drilling and blasting [2]. A pattern of holes is drilled into the rock face using compressed air drills. Engineers stand on a moving carriage, called a "jumbo", running on temporary rails. A drill tipped with a tungsten carbide bit can penetrate up to 3m of rock in five minutes. When a round of holes is ready, the engineers place explosives in them. The tunnel is evacuated and the explosives detonated. A mobile rock shovel lifts the shattered rock into dumper cars which are then removed.

Soft material such as sandstone, clay and chalk is removed by automatic machines [Key]. Machines of this type have a hydraulically-powered cutting head fitted with teeth or rock-cutting bits. The head rotates slowly and is driven forwards into the face. The debris falling from the cutting face is removed to the surface by a conveyor system. As the cutting head advances, engineers follow behind buttressing the freshly-exposed rock with prefabricated concrete sections.

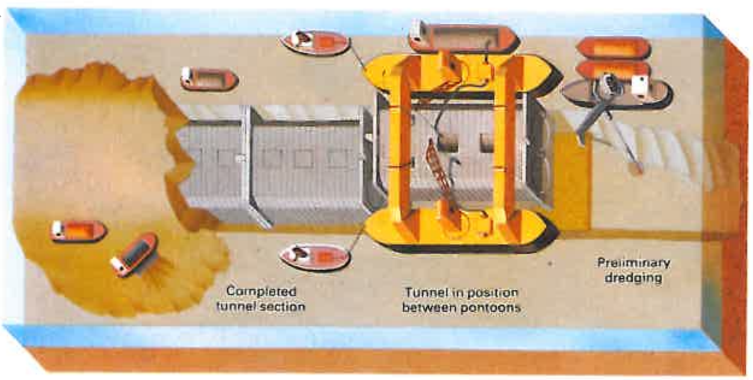
Shallow tunnels are sometimes built by the "cut and cover" method. A deep trench is excavated. The tunnel lining is placed in the trench, complete with a roof. The tunnel is then covered with excavated material. Underwater tunnels are built in a similar manner. Prefabricated tunnel sections are floated into position above a previously excavated trench on the sea or river bed. The floats supporting the tunnel are removed and it sinks into the trench. The individual sections are joined and sealed underwater [4, 8].

In underwater tunnelling, the working area is pressurized so that the internal air pressure exceeds the pressure of water. The engineers put the tunnel in position and cover it with cement grout (a sealing mixture) to make it watertight.

KEY

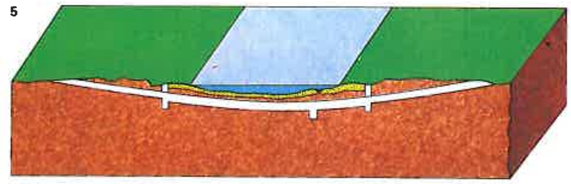
The Mersey Mole is a tunnelling machine designed for excavating soft rock. It was used in 1967 to cut a 10.3m diameter tunnel beneath the River Mersey at Liverpool, England. The mole is capable of cutting away the rock surface and then conveying it back to skips running on rails. In addition, the mole contains gear for positioning concrete lining sections.

4



4 Underwater tunnels are increasingly being built by the immersed tube method. Prefabricated steel or concrete sections of tunnel are sealed at the ends and floated into position. There they are sunk into a trench dredged into the bed of the lake or river. The sections are then joined together end to end with watertight joints and covered with previously dredged material. It is economical to make all the tunnel sections close to the tunnel site and factories for this purpose may be built on the shore; the tunnel sections are floated to the site on barges. Alternatively, prefabricated concrete or steel tunnel sections can be made in a floating dry dock that is moored alongside the site at which they are to be sunk into the dredged trench.

5

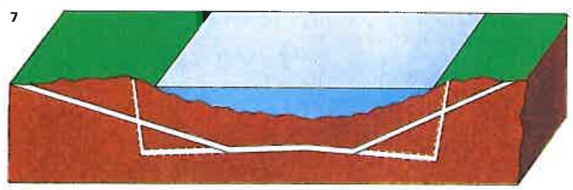


5 The first Mersey road tunnel at Liverpool, England, is shown here in cross-section. The tunnel falls steadily from its portals to a central point where pumps operate to remove any water that may have seeped in. It has a diameter of 13.5m and carries four traffic lanes (with additional unused space, provided below, for two double-decker tramway lines). The tunnel was hand-excavated in four stages. First of all, two tunnels were cut, one above the other. After this, the entire tunnel was opened out, top half first. Completed in 1934, the tunnel runs for a distance of 3.2km, half of it under water.

6

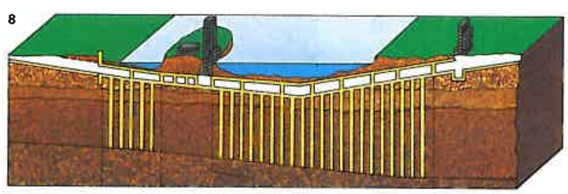
6 The Chesapeake Bay bridge-tunnel was one of the boldest underwater tunnel projects and a remarkable feat of engineering. The 2km tunnel runs between two man-made islands built of sand, stone and concrete. It passes under one of three shipping lanes along the 28km causeway, which crosses Chesapeake Bay on the east coast of the USA. It is accompanied by a second tunnel of similar size and design. At the eastern end of the structure, situated between two more islands, is a high-level bridge. Each of the four islands is approximately 450m long and 70m wide. The two tunnels were constructed by sinking prefabricated, double-skinned steel tubes into a dredged trench.

7



7 The Seikan railway tunnel is nearly 54km long and links Japan's main island of Honshu with the northern island of Hokkaido. Construction was very difficult because of adverse geological conditions. Although 100m of rock cover the tunnel under the deepest water, the danger of a leak at high pressure prompted the designers to extend the low section to a lower level at each end, providing a major drain-off facility to the high-power pumping plant. Most of the tunnel runs through rock which was excavated using rock-tunnelling machines.

8



8 The four-lane road tunnel under the River Ij in Amsterdam was completed in 1967. The immersed tube method of construction was mainly used, although the section concerned in ventilation was built on site. The prefabricated, reinforced-concrete tunnel elements were between 70 and 90m long and weighed up to 17,000 tonnes. They were designed as a flat box with two 7m roadways running side by side. There are both service ducts running in between them and ventilation ducts below them. Due to the instability of the river bed, however, the tunnel sections had to be laid onto sliding plastic bearings on a concrete raft, which was in turn supported by long piles. The tunnel sections were waterproofed with a bituminous membrane and a steel skin.

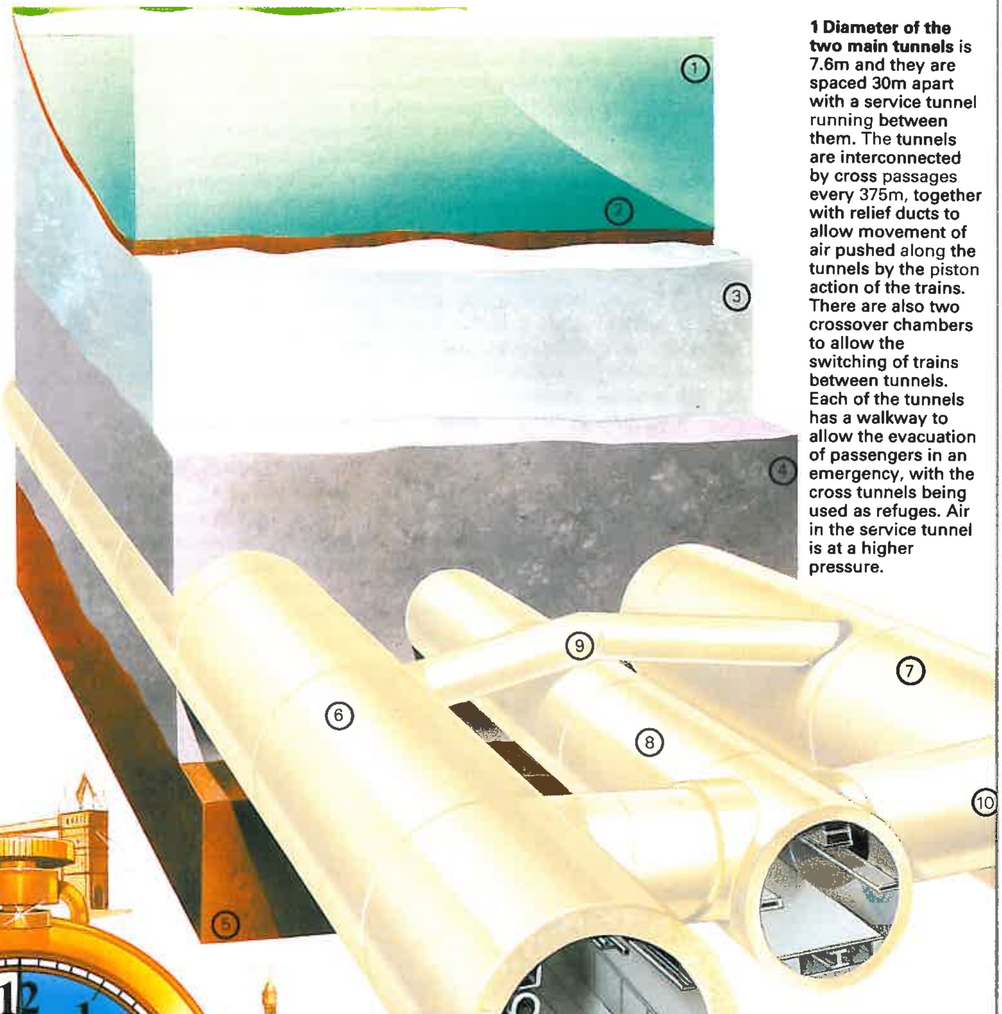
The Channel Tunnel

The first serious suggestion for a tunnel between France and England was made in 1802, and the first tunnelling attempt was undertaken 80 years later. Although operations proceeded successfully – reaching nearly 3km from shore – political (and military) objections led to the project being stopped. Another attempt in 1974 was abandoned for financial reasons.

However, the obvious advantages of such a link meant there was continued interest and during the 1980s the British and French governments agreed on the construction of a fixed link financed as a private venture. After appraisal of various proposals (for both bridges and tunnels) the Eurotunnel consortium was granted a concession to build and operate a tunnel over a period of 55 years.

The chosen design is for a rail-only link running in twin tunnels between terminals near Folkstone in England and Calais in France. Road vehicles will be carried between the terminals on special shuttle trains and there will be through passenger and freight trains. Tunnelling started in 1987 and services are planned to start in 1993.

1



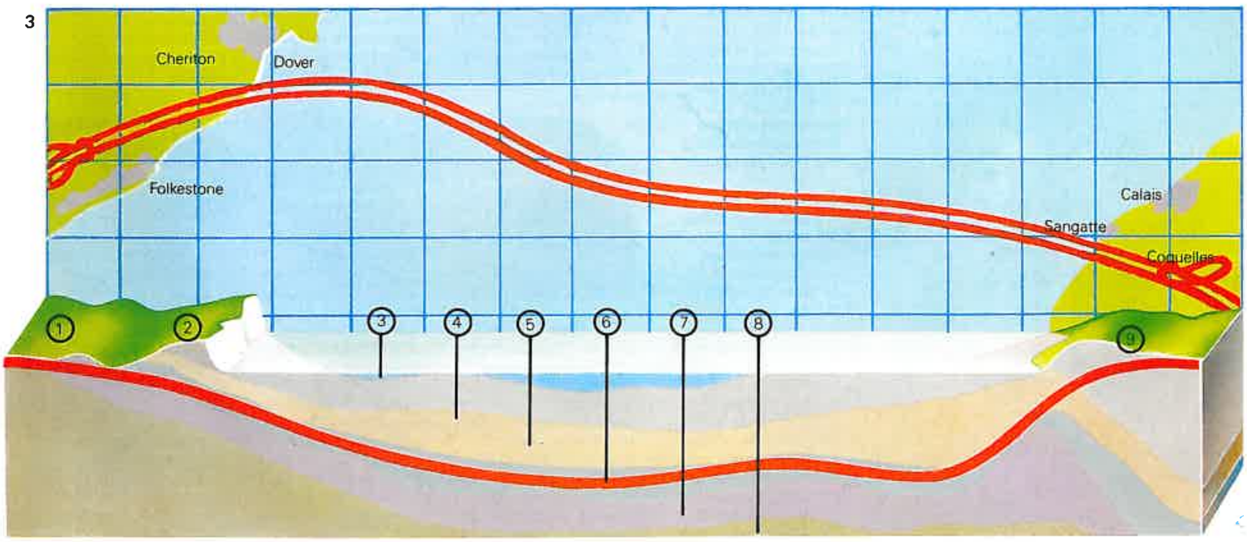
1 Diameter of the two main tunnels is 7.6m and they are spaced 30m apart with a service tunnel running between them. The tunnels are interconnected by cross passages every 375m, together with relief ducts to allow movement of air pushed along the tunnels by the piston action of the trains. There are also two crossover chambers to allow the switching of trains between tunnels. Each of the tunnels has a walkway to allow the evacuation of passengers in an emergency, with the cross tunnels being used as refuges. Air in the service tunnel is at a higher pressure.

1 Sea
2 Sea bed
3 Lower chalk
4 Chalk marl
5 Gault clay
6 Train tunnel (running tunnel)
7 Train tunnel (running tunnel)
8 Service tunnel
9 Piston relief duct
10 Connecting passage (cross passage)
11 Passenger car shuttle
12 Electric train

2

2 High-speed rail links for through trains will give a travel time between London and Paris of around three hours, as shown by the hands on the watch. This is much the same as the time taken travelling by air and significantly faster than journeys made using hovercraft and conventional ferries for the Channel crossing. The tunnel will link the UK to the continental rail network, allowing direct freight services. Shuttle services for car and coach traffic are planned to operate at 12-minute intervals in times of peak demands, with a terminal to terminal travel time of under 35 minutes. Frontier formalities will be carried out at the departure terminal so cars will drive off directly on arrival.

3



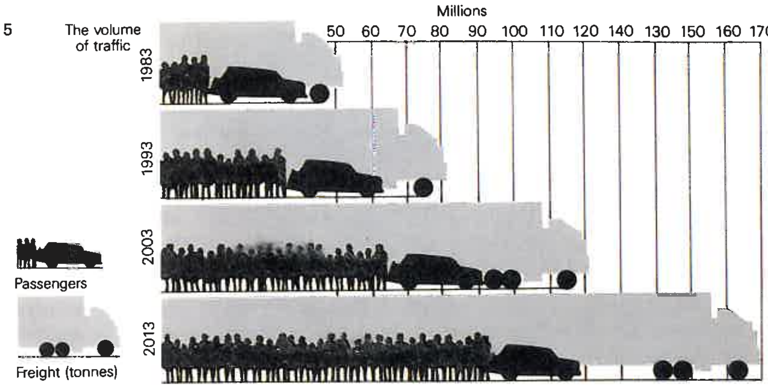
3 Tunnel terminals are at Folkestone, near Dover, and Coquelles, near Calais. The tunnels are nearly 50km long with 38km lying under the sea. For most of this distance the route runs through a layer of chalk marl approximately 100m below sea level. The marl is a mixture of clay and chalk and is excellent for easy tunnelling.

1 Britain
2 Shakespeare Cliff
3 Sea level
4 Sea bed
5 Lower chalk
6 Chalk marl
7 Gault clay
8 Greensand
9 France

4 Double-deck shuttle wagons are used to transport cars, with coaches and caravans being carried on single-deck wagons. Travellers arriving at the terminals buy their tickets (no booking is needed) and drive straight on to the shuttles at the terminals, after passing through immigration and custom formalities. The shuttles are well lit and ventilated and the drivers and passengers remain in their vehicles, with attendants on the shuttles providing any assistance needed. Special freight shuttles are used for lorries and other commercial vehicles.

5 Cross-Channel traffic, for both freight and passengers, is forecast to increase significantly towards the end of the century, more than doubling between 1983 and 2003. Initially the tunnel is expected to carry 29 million passengers a year on the shuttles, and through trains.

5



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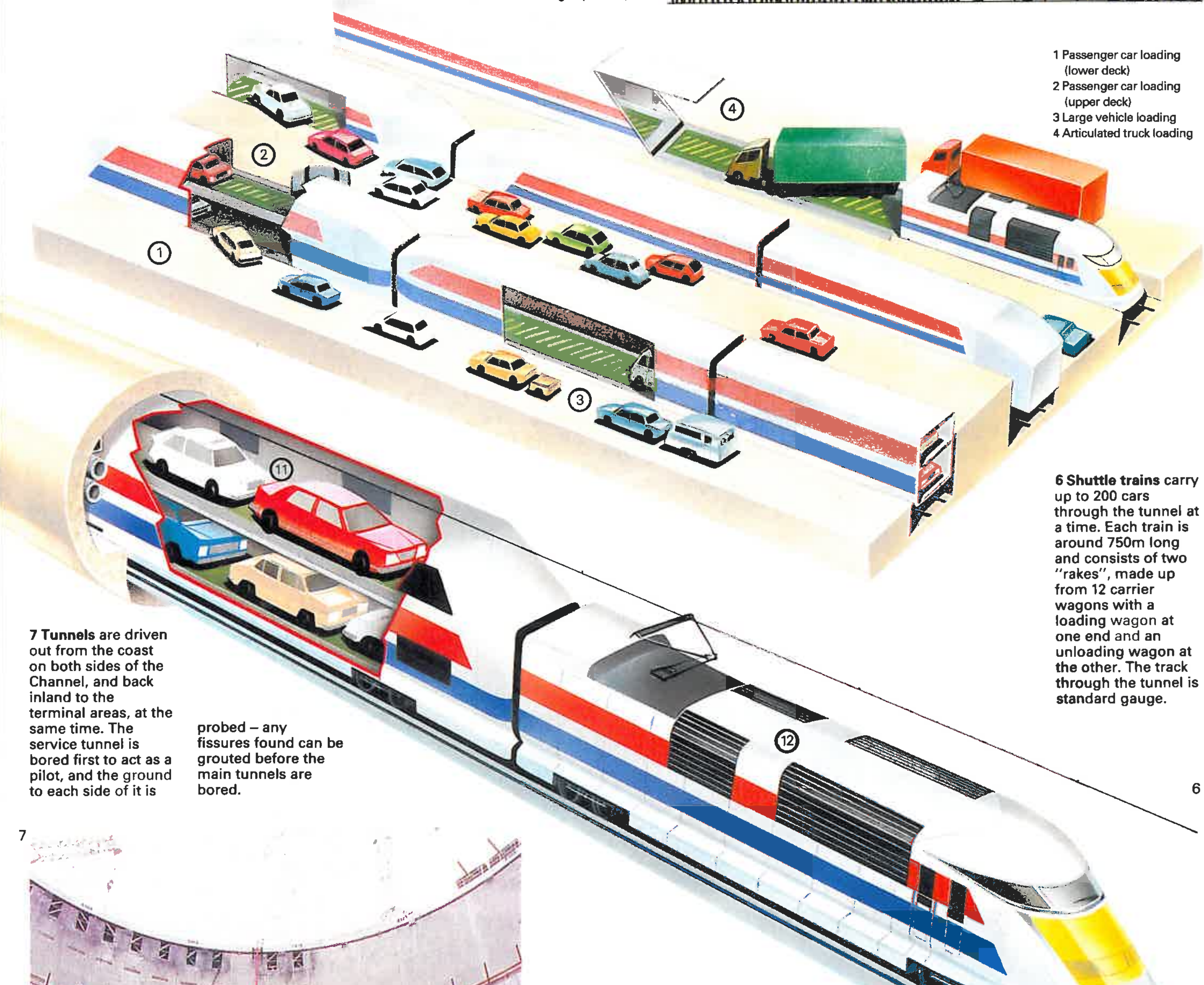


6

6 Shuttle trains carry up to 200 cars through the tunnel at a time. Each train is around 750m long and consists of two "rakes", made up from 12 carrier wagons with a loading wagon at one end and an unloading wagon at the other. The track through the tunnel is standard gauge.

7 Tunnels are driven out from the coast on both sides of the Channel, and back inland to the terminal areas, at the same time. The service tunnel is bored first to act as a pilot, and the ground to each side of it is probed – any fissures found can be grouted before the main tunnels are bored.

7

8

8 Tunnel boring machines have rotating heads with hard tungsten carbide picks that cut into the rock. Spoil is carried to the back of the machine using a conveyor system and loaded on a service train, which takes it out of the tunnel for disposal. As the tunnel advances it is lined with pre-fabricated segments.

Modern bridges

Two nineteenth-century inventions led to a revolution in bridge building. These were Portland cement and mass-produced steel. Cement is the vital ingredient of concrete, and mass concrete can be used to build piers, abutments (bank supports) and arches of "artificial" stone to any required shape. Well-made concrete is extremely strong in compression (when squeezed) but it has very little strength in tension (when stretched). On the other hand, steel can withstand great tension as well as compression, and can be used for building girders of far greater strength than the wooden trusses of early days. High-tensile steel wire cables can be slung between tall towers to support immense suspension bridges.

Reinforced concrete bridges

These new materials, concrete and steel, can also be used in combination with each other. For example, a concrete structure does not have to be designed so that the material is entirely in compression, because steel rods can be used to carry the tension.

The French engineer Eugene Freyssinet (1879-1962) overcame the remaining weakness of reinforced concrete (the fact that steel in tension stretches, allowing the concrete immediately around the steel to stretch and frequently to crack) by using high-strength tensioned steel wires as the reinforcement. This technique permitted Freyssinet to "pre-stress" concrete (pre-load it in compression), so that it would never be subjected to tension at all. The result was a material so versatile that it could be used to make stronger, lighter and more architecturally satisfactory bridges.

Types of bridge

There are four basic types of bridge: beam, arch, suspension and cantilever [1]. The beam bridge is, in effect, a pair of girders supporting a deck spanning the gap between two piers. Such a beam has to withstand both compression in its upper parts and tension in its lower parts. Where it passes over supports other forces come into play. For example, if the beam is continuous above the pier the top section is in tension and the bottom in compression. Most of the strength is needed in these top and bottom sections, and bridge beams may be hollow box girders or open frame trusses. The span of a beam bridge is limited by the strength needed to prevent the beam bending under its own weight between the piers. The stayed beam bridge offers longer spans by using stays angled down from one or more towers to support the beam instead of intermediate piers.

An arch bridge can be designed so that no part of it has to withstand tension. Concrete is therefore well suited to arched bridge design. When reinforced concrete is used, a more elegant and sometimes less costly bridge can be designed with arches that are relatively shallow in relation to their span [4]. Virtually all concrete bridges are reinforced and may be cast in position or built up from pre-cast sections [3].

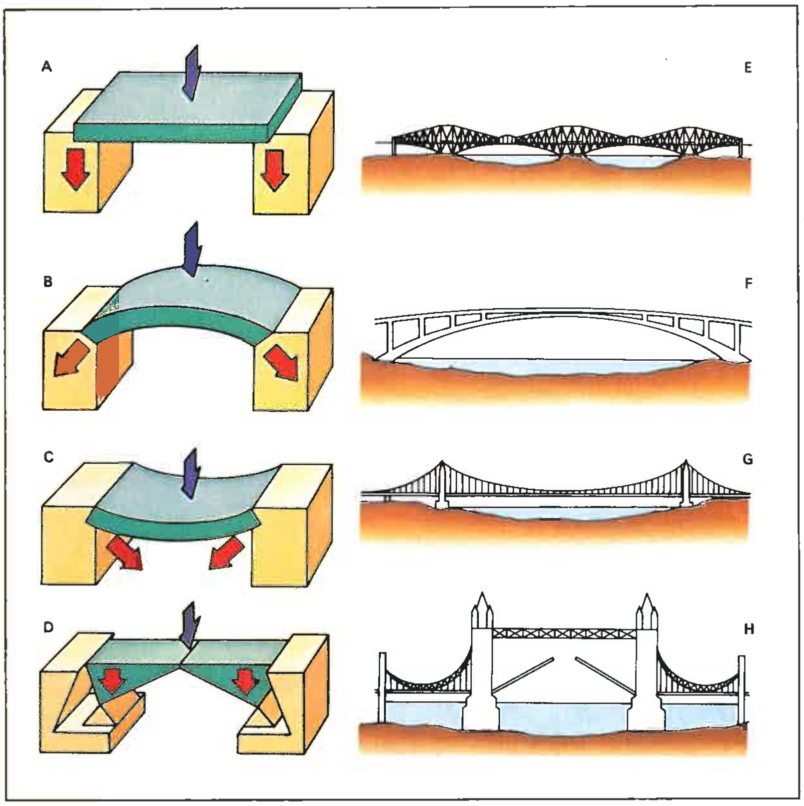
A suspension bridge consists, basically, of a deck suspended from two or more cables slung between high towers. The cables are made up from a large number of strands of high-tensile steel wire and the pull on them is taken by massive anchorages at the ends. The supporting towers are in compression

CONNECTIONS

See also
Traffic engineering

In other volumes
Machines for lifting (6)
History of bridges (9)

1

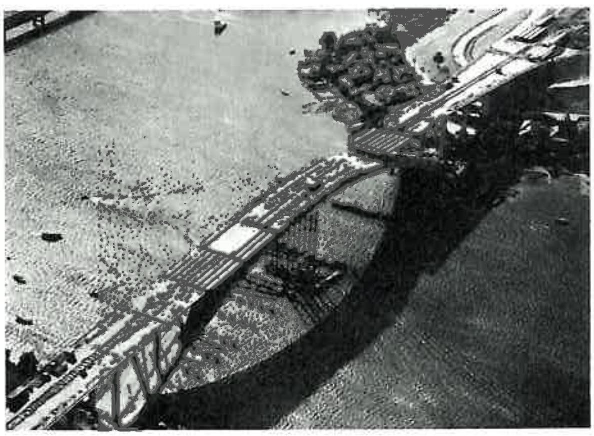


1 Bridges are of four main types: the beam bridge [A], the arch bridge [B], the suspension bridge [C] and the cantilever bridge [D]. The three main structures of the Forth railway bridge [E] are cantilevers and the two steel trusses that connect them are end-supported beams. In [F] it is the lower member that forms the arch. The suspension bridge [G] has its roadway hanging from enormous steel cables passing over tall towers. The two rising arms of Tower Bridge in London [D, H] are cantilevers, whereas the slender truss which connects the top of the towers is a long beam

2

2 The Howrah Bridge in Calcutta is a typical steel truss cantilever bridge spanning a distance of 453m. The two main piers of this bridge were built hollow and had 21 vertical shafts. By digging out the sand at the bottom of these shafts, the piers were made to sink steadily down until they reached a secure bas of impervious clay. The bridge was opened in 1943.

3



3 The Gladesville Bridge over the Parramatta River at Sydney, Australia, is a 305m span concrete arch with a height of 41m. It was formed from pre-cast elements erected on a steel centring.

4

4 The Medway Bridge in south-east England is a pre-stressed concrete cantilever design. The main span of 150m is achieved by two 60m cantilever arms and a 30m central suspended beam with an arch depth of 2.2m.

and the deck – generally an aerodynamic box section – is supported at frequent intervals by hangers from the cables.

A cantilever bridge consists of two arms supported at their ends and extended to meet one another. Normally there is a gap between the ends of the arms and this is filled with a simple suspended span. In many cantilever designs two arms are cantilevered out in opposite directions from a supporting pier so that they balance one another.

Not all bridges are fixed structures; where there is limited headroom for shipping part of the structure may be made moveable. In some designs like London's Tower Bridge the central span is formed from counter-balanced cantilever arms, or bascules, that pivot upwards. Other designs have spans that pivot sideways or are lifted vertically.

There is more to a bridge than the main span and without proper foundations for the piers or towers the whole structure would fail. Most modern bridges have reinforced concrete foundations, often keyed into bedrock. They may have to be designed to withstand the scouring action of tides, buffeting from pack ice and even mild earthquake tremors. If solid bedrock is too deep to be reached by excavating, foundations can be built on piles driven into the subsoil.

Theoretical limits of bridge spans

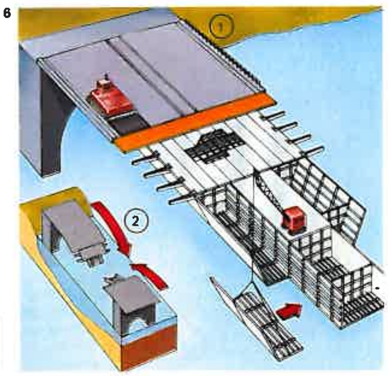
A bridge carries two loads. The useful load is the live load of crossing traffic. In addition it must carry its own weight, the dead load. The longer the span of a bridge, the greater its dead load; consequently there is a theoretical span limit for any given material and method of construction. For example the theoretical limit for steel arch bridges is around 1,000m, twice as large as current designs. Here the main restrictions are financial, with other designs such as the suspension bridge offering more economic ways of spanning wide gaps. The Humber Bridge has a main span of 1,410m whereas the Akashi-Kaikyo bridge between the islands of Honshu and Shikoku, Japan, has a design span of 1,980m. The use of modern materials makes even larger spans possible. One proposed design for a bridge across the English Channel has 5km spans supported by synthetic fibre cables.

KEY

Suspension bridges are usually erected when very long spans are involved or when the soil is too unstable to support the piers. One of the longest suspension bridges in the world crosses the River Humber at Hull. It covers a span of 1,410m from one support tower to the other. The bridge deck is an aerodynamically shaped box girder. The design is economical in its use of material, thus reducing the load carried by the cables and towers.

5

6



5 Motorway interchanges are designed to allow the free flow of traffic without intersections and this involves the use of a lot of bridges together with elevated viaducts. Most of these bridges are of the simple beam type and reinforced concrete construction is widely used, either as prefabricated sections or cast in position. When motor-ways are constructed, bridges have to be built before roads.

6 Box girder bridges are increasingly used today because of their high strength-to-weight ratio. Building a bridge of this type often involves construction outwards from a support [1] in the form of long cantilevers. The method imposes stresses [2] on the structure which will not occur when it is complete, and it is vital for these to be adequately allowed for. Once complete, the bridge assumes its designed strength.

7

7 The Sydney Harbour Bridge is a steel arch opened in 1932 and carries a combination of urban rail and road lanes over a clear span of 508m. It has a width of 49m and a deck height of 52m.

8 The siting of new motorways often presents difficulties, with protests from environmentalists and landowners. Here in Italy the Brenner motorway is being constructed on stilts alongside a railway, so making double use of an existing route.

8