Geophysical and Tunnel Engineering

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Table of Contents

Chapter 1 - Retaining Wall

Chapter 2 - Caisson (Engineering)

Chapter 3 - Engineering Geology

Chapter 4 - Levee Breach

Chapter 5 - Infill

Chapter 6 - Shaft Construction

Chapter 7 - Shoring

Chapter 8 - Soil Gradation

Chapter 9 - Suction Excavator

Chapter 10 - Well Logging

Chapter 11 - Tunnel

Chapter 12 - Wind Tunnel

Chapter 13 - Subsonic and Transonic Wind Tunnel

Chapter 14 - Vertical Wind Tunnel & Supersonic Wind Tunnel

Chapter 15 - Tunnel Boring Machine

Chapter 16 - Submerged Floating Tunnel

Chapter 17 - Culvert

Chapter 18 - Immersed Tube

Chapter 1

Retaining Wall

A gravity-type stone retaining wall

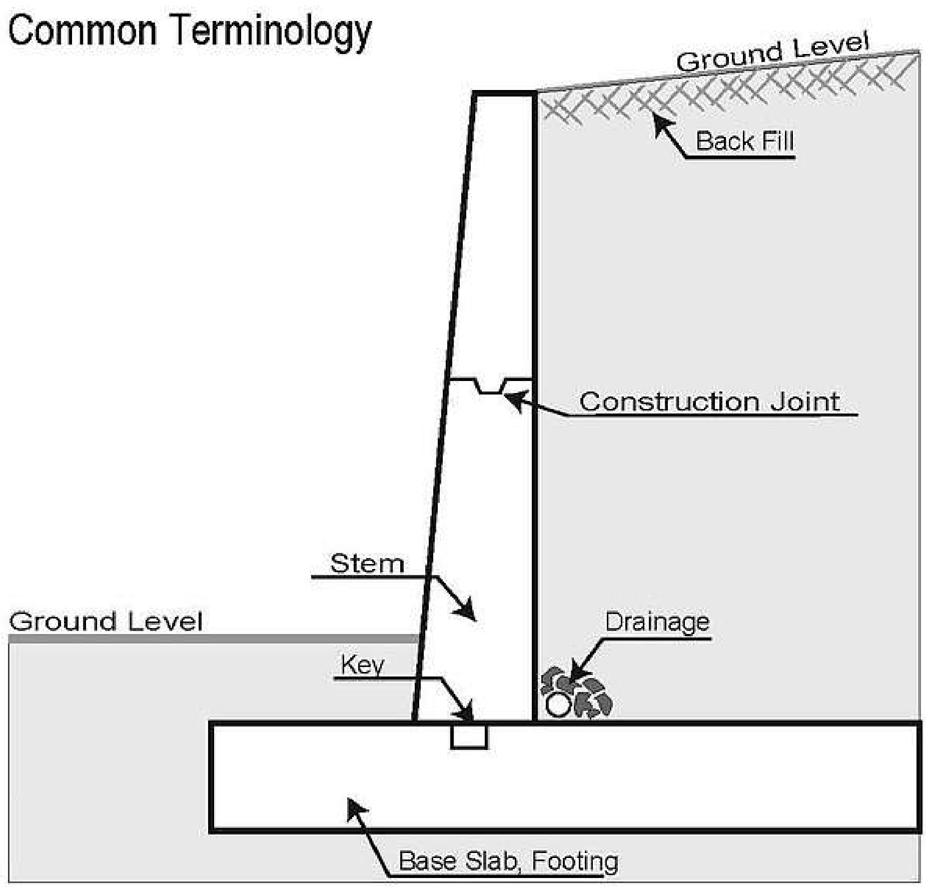
Retaining walls are built in order to hold back ground which would otherwise move downwards. Their purpose is to stabilise slopes and provide useful areas at different elevations, e.g. terraces for agriculture, buildings, roads and railways.

Definition

A **retaining wall** is a structure designed and constructed to resist the lateral pressure of soil when there is a desired change in ground elevation that exceeds the angle of repose of the soil.

The basement wall is thus one form of retaining wall.

However, the term is most often used to refer to a cantilever retaining wall, which is a freestanding structure without lateral support at its top.



Typically retaining walls are cantilevered from a footing extending up beyond the grade on one side and retaining a higher level grade on the opposite side. The walls must resist the lateral pressures generated by loose soils or, in some cases, water pressures.

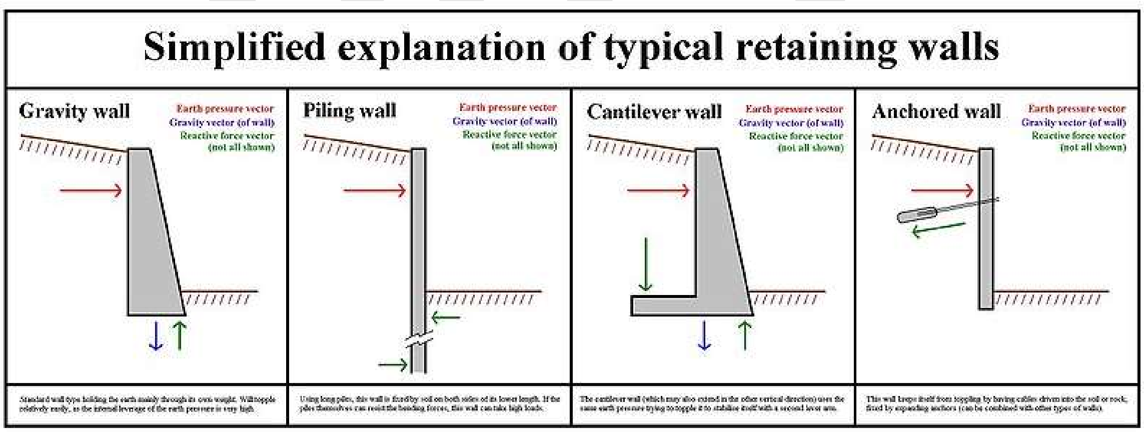
The most important consideration in proper design and installation of retaining walls is to recognize and counteract the fact that the retained material is attempting to move forward and downslope due to gravity. This creates lateral earth pressure behind the wall which depends on the angle of internal friction (phi) and the cohesive strength (c) of the retained material, as well as the direction and magnitude of movement the retaining structure undergoes.

Lateral earth pressures are zero at the top of the wall and - in homogenous ground - increase proportionally to a maximum value at the lowest depth. Earth pressures will push the wall forward or overturn it if not properly addressed. Also, any groundwater behind the wall that is not dissipated by a drainage system causes hydrostatic pressure on the wall. The total pressure or thrust may be assumed to act at one-third from the lowest depth for lengthwise stretches of uniform height.

Unless the wall is designed to retain water, It is important to have proper drainage behind the wall in order to limit the pressure to the wall's design value. Drainage materials will reduce or eliminate the hydrostatic pressure and improve the stability of the material behind the wall. Drystone retaining walls are normally self-draining.

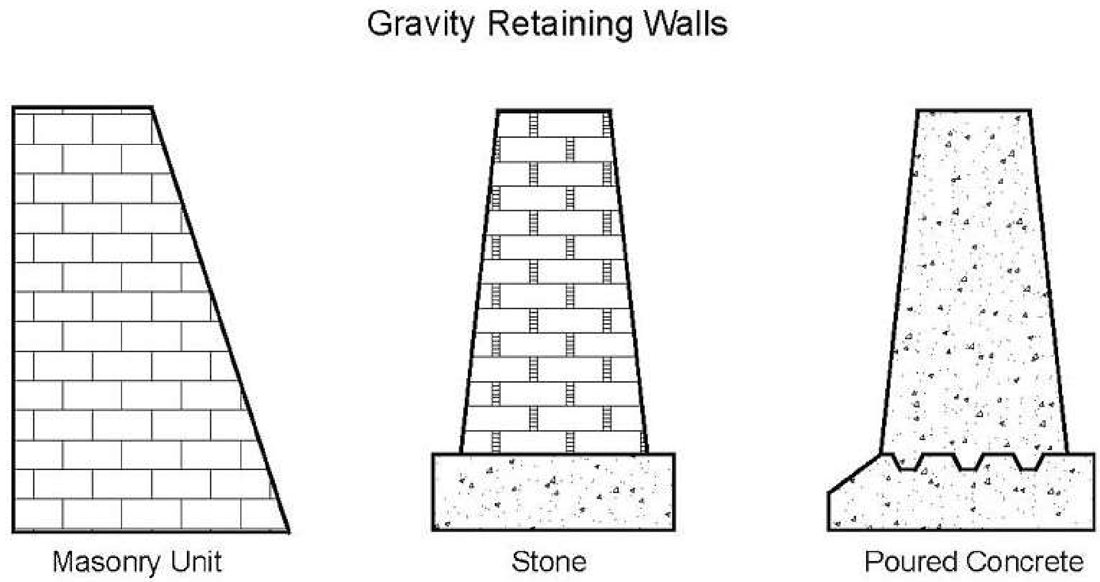
As an example, the International Building Code requires retaining walls to be designed to ensure stability against overturning, sliding, excessive foundation pressure and water uplift; and that they be designed for a safety factor of 1.5 against lateral sliding and overturning.

Types



Various types of retaining walls

Gravity

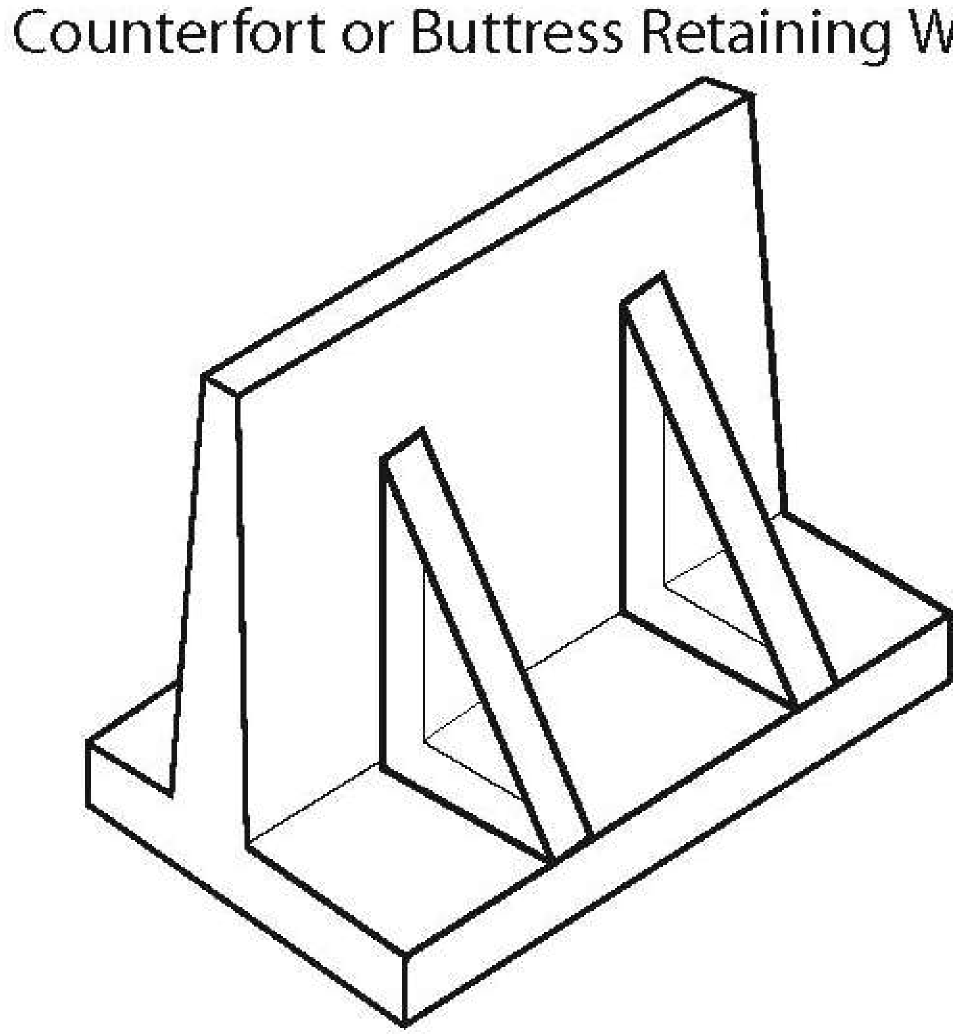


Construction types of gravity retaining walls

Gravity walls depend on the weight of their mass (stone, concrete or other heavy material) to resist pressures from behind and will often have a slight 'batter' setback, to improve stability by leaning back into the retained soil. For short landscaping walls, they are often made from mortarless stone or segmental concrete units (masonry units). Dry-stacked gravity walls are somewhat flexible and do not require a rigid footing in frost areas. Home owners who build larger gravity walls that do require a rigid concrete footing can make use of the services of a professional excavator, which will make digging a trench for the base of the gravity wall much easier.

Earlier in the 20th century, taller retaining walls were often gravity walls made from large masses of concrete or stone. Today, taller retaining walls are increasingly built as composite gravity walls such as: geosynthetic or with precast facing; gabions (stacked steel wire baskets filled with rocks); crib walls (cells built up log cabin style from precast concrete or timber and filled with soil); or soil-nailed walls (soil reinforced in place with steel and concrete rods).

Cantilevered



Conterfort/Buttress on Cantilevered Wall

Cantilevered retaining walls are made from an internal stem of steel-reinforced, cast-in-place concrete or mortared masonry (often in the shape of an inverted T). These walls cantilever loads (like a beam) to a large, structural footing, converting horizontal pressures from behind the wall to vertical pressures on the ground below. Sometimes cantilevered walls are butressed on the front, or include a counterfort on the back, to improve their strength resisting high loads. Buttresses are short wing walls at right angles to the main trend of the wall. These walls require rigid concrete footings below seasonal frost depth. This type of wall uses much less material than a traditional gravity wall.

Sheet piling

Sheet pile wall

Sheet pile retaining walls are usually used in soft soils and tight spaces. Sheet pile walls are made out of steel, vinyl or wood planks which are driven into the ground. For a quick estimate the material is usually driven 1/3 above ground, 2/3 below ground, but this may be altered depending on the environment. Taller sheet pile walls will need a tie-back anchor, or "dead-man" placed in the soil a distance behind the face of the wall, that is tied to the wall, usually by a cable or a rod. Anchors are placed behind the potential failure plane in the soil.

Anchored

An anchored retaining wall can be constructed in any of the aforementioned styles but also includes additional strength using cables or other stays anchored in the rock or soil behind it. Usually driven into the material with boring, anchors are then expanded at the end of the cable, either by mechanical means or often by injecting pressurized concrete, which expands to form a bulb in the soil. Technically complex, this method is very useful where high loads are expected, or where the wall itself has to be slender and would otherwise be too weak.

Alternative Retaining Techniques

Soil nailing

Soil nailing is a technique in which soil slopes, excavations or retaining walls are reinforced by the insertion of relatively slender elements - normally steel reinforcing bars. The bars are usually installed into a pre-drilled hole and then grouted into place or drilled and grouted simultaneously. They are usually installed untensioned at a slight downward inclination. A rigid or flexible facing (often sprayed concrete) or isolated soil nail heads may be used at the surface.

Soil-strengthened

A number of systems exist that do not simply consist of the wall itself, but reduce the earth pressure acting on the wall itself. These are usually used in combination with one of the other wall types, though some may only use it as facing (i.e. for visual purposes).

Gabion meshes

This type of soil strengthening, often also used without an outside wall, consists of wire mesh 'boxes' into which roughly cut stone or other material is filled. The mesh cages reduce some internal movement/forces, and also reduce erosive forces.

Mechanical stabilization

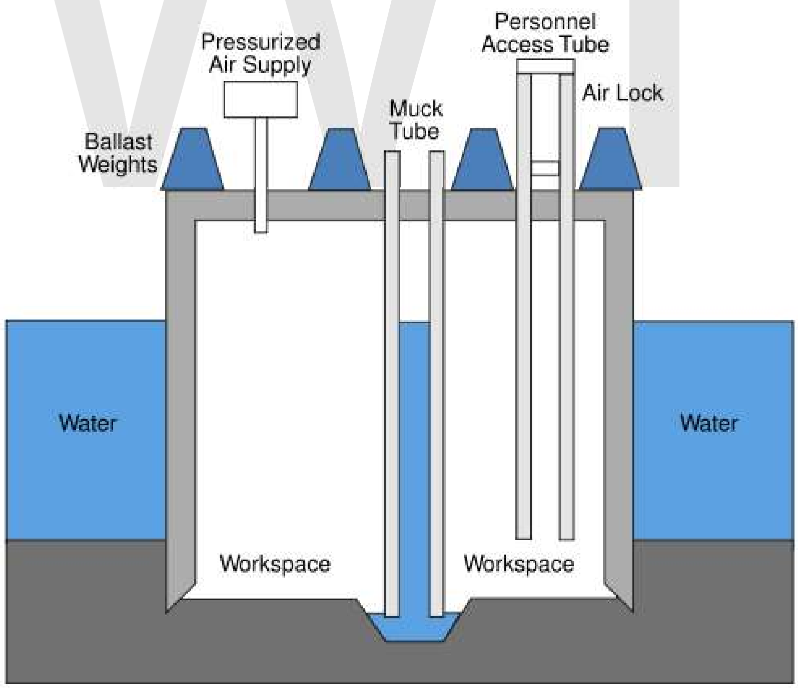
Mechanically stabilized earth, also called MSE, is soil constructed with artificial reinforcing via layered horizontal mats (geosynthetics) fixed at their ends. These mats provide added internal shear resistance beyond that of simple gravity wall structures. Other options include steel straps, also layered. This type of soil strengthening usually needs outer facing walls (S.R.W.'s - Segmental Retaining Walls) to affix the layers to and vice versa.

The wall face is often of precast concrete units that can tolerate some differential movement. The reinforced soil's mass, along with the facing, then acts as an improved gravity wall. The reinforced mass must be built large enough to retain the pressures from the soil behind it. Gravity walls usually must be a minimum of 50 to 60 percent as deep or thick as the height of the wall, and may have to be larger if there is a slope or surcharge on the wall.

Chapter 2

Caisson (Engineering)

In geotechnical engineering, a **caisson** is a retaining, watertight structure used, for example, to work on the foundations of a bridge pier, for the construction of a concrete dam, or for the repair of ships. These are constructed such that the water can be pumped out, keeping the working environment dry. When piers are to be built using an open caisson and it is not practical to reach suitable soil, friction pilings may be driven to form a suitable sub-foundation. These piles are connected by a foundation pad upon which the column pier is erected.



Schematic cross section of a pressurized caisson

Shallow caissons may be open to the air, whereas **pneumatic caissons**, which penetrate soft mud, are sealed at the top and filled with compressed air to keep water and mud out at depth. An airlock allows access to the chamber. Workers move mud and rock debris (called *muck*) from the edge of the workspace to a water-filled pit, connected by a tube (called the *muck tube*) to the surface. A crane at the surface removes the soil with a clamshell bucket. The water pressure in the tube balances the air pressure, with excess air escaping up the muck tube. The pressurized air flow must be constant to ensure regular air changes for the workers and prevent excessive inflow of mud or water at the base of the caisson.

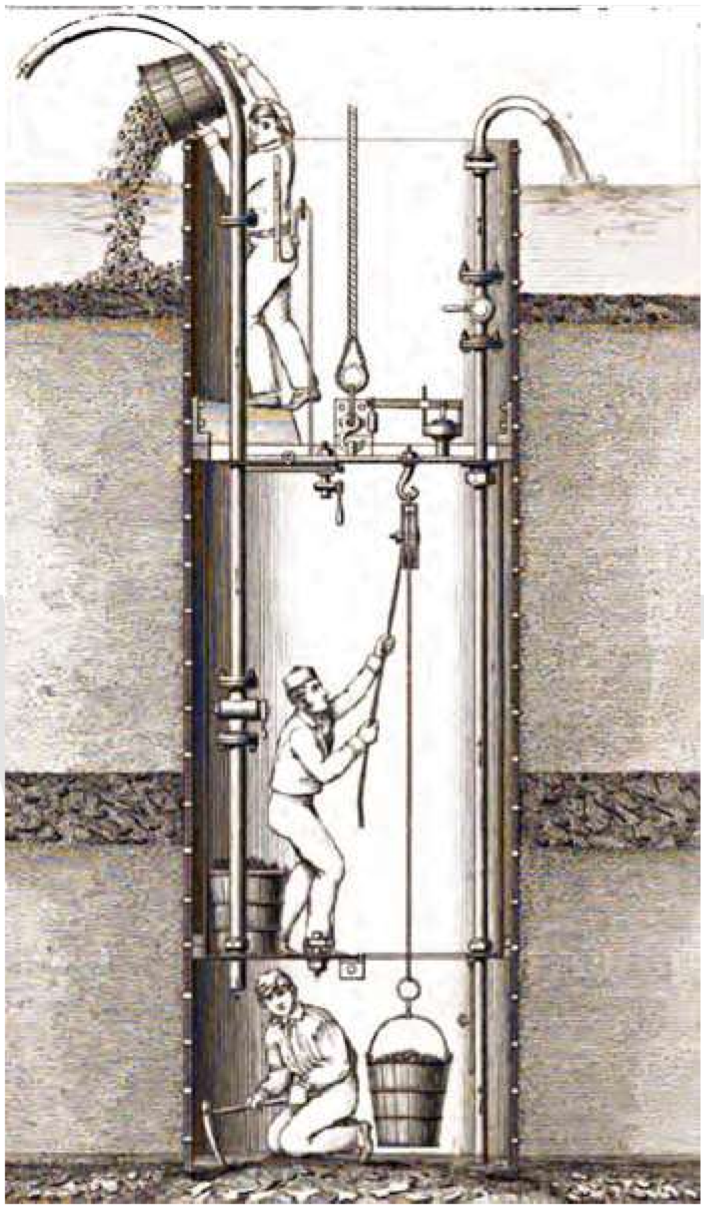
The caisson will be brought down through soft mud until a suitable foundation material is encountered. While bedrock is preferred, a stable, hard mud is sometimes used when bedrock is too deep.

Caisson disease is so named since it appeared in construction workers when they left the compressed atmosphere of the caisson and rapidly reentered normal (decompressed) atmospheric conditions. It is caused by the same processes as decompression sickness in divers. Construction of the Brooklyn Bridge, which was built with the help of caissons, resulted in numerous workers being either killed or permanently injured by caisson disease during its construction, including the designer's son and Chief Engineer of the project, Washington Roebling.

Caissons have also been used in the installation of hydraulic elevators where a single-stage ram is installed below the ground level.

Caissons, codenamed *Phoenix*, were an integral part of the Mulberry harbours used during the World war II Allied invasion of Normandy.

Types



A diagram of an open caisson, dated 1846

The four main types of caisson are *box caisson*, *open caisson*, *compressed-air caisson* and *monolith caisson*.

Box

Box caissons are prefabricated concrete boxes with sides and bottom and are set down on prepared bases. Once in place they will be filled with concrete to become part of the permanent works, for example the foundation for a bridge pier. One problem with box caissons is that hollow concrete structures float and so they must be ballasted or anchored to prevent this until they can be filled with concrete. Adjustable anchoring systems combined with a GPS survey allow engineers to position a box caisson with pinpoint accuracy. Elaborate anchoring systems may be required in tidal zones.

Open

Open caissons are similar to box caissons except that they do not have a bottom face. They are suitable for use in soft clays (e.g. in some river-beds) but not for where there may be large obstructions in the ground. Open caissons used in soft grounds or high water tables, where open trench excavations are impractical, can also be used to install deep manholes, pump stations and reception/launch pits for micro tunnelling, pipe jacking and other operations. The open caissons may fill with water during sinking. The material is excavated by clamshell excavator bucket on crane. The caissons are sunk by self-weight, concrete or water ballast placed on top, or by hydraulic jacks. The leading edge of the caisson or "cutting shoe" is sloped out at a sharp angle (usually made of steel) to aid sinking in a vertical manner. The shoe is generally wider than the caisson to reduce friction and the leading edge may be supplied with pressurised bentonite slurry (it swells in water to stabilise settlement or fill depressions/voids). The formation level subsoil may still not be suitable for excavation or bearing capacity. The water in the caisson (due to high water table) balances the upthrust forces of the soft soils underneath. If dewatered, the base may "pipe" or "boil" and the caisson sink. To combat this problem piles may be driven from the surface. H-beam sections (typical column sections, due to resistance to bending in all axes) may be driven at angles "raked" to rock or other firmer soils. The H-beams are left extended above the base. A reinforced concrete plug is poured under the water known as a "tremie pour". This will act as a pile cap and resist the upward forces of subsoil once dewatered. The piles will act as bearing (transmitting load to deeper soils or friction along their surface length) and anchorage (resist floatation in the same manner).

Compressed-air

Compressed-air caissons have the advantage of providing dry working conditions which are better for placing concrete. They are also well suited for foundations for which other methods might cause settlement of adjacent structures.

Monolithic

Monoliths are, as their name suggests, larger than the other types but are similar to open caissons. They are often found in quay walls where resistance to impact from ships is required.

Boat lift caissons

The word *caisson* is also used as a synonym for the water-filled trough part of caisson locks, canal lifts and inclines in which boats and ships rest whilst being lifted from one canal elevation to another. This is the opposite of the caissons mentioned earlier; the water is retained on the inside of the caisson, not excluded from the caisson.

Ventilation filtration systems

The word *caisson* is also used as a name for an airtight housing for ventilation filters in facilities that handle hazardous materials. The housing usually has an upstream compartment for a pre-filter element and a downstream compartment for a high-efficiency filter element. It may have multiple sets of compartments. The housing has gasketed access doors to allow for the change out of the filter elements. The housing is usually equipped with connection points used to test the efficiency of the filters and monitor changes in the differential pressure across the filter media.

Chapter 3

Engineering Geology

Engineering Geology is the application of the geologic sciences to engineering practice for the purpose of assuring that the geologic factors affecting the location, design, construction, operation and maintenance of engineering works are recognized and adequately provided for. Engineering geologists investigate and provide geologic and geotechnical recommendations, analysis, and design associated with human development. The realm of the engineering geologist is essentially in the area of earth-structure interactions, or investigation of how the earth or earth processes impact human made structures and human activities.

Engineering geologic studies may be performed during the planning, environmental impact analysis, civil or structural engineering design, value engineering and construction phases of public and private works projects, and during post-construction and forensic phases of projects. Works completed by engineering geologists include; geologic hazards, geotechnical, material properties, landslide and slope stability, erosion, flooding, dewatering, and seismic investigations, etc. Engineering geologic studies are performed by a geologist or engineering geologist that is educated, trained and has obtained experience related to the recognition and interpretation of natural processes, the understanding of how these processes impact man-made structures (and vice versa), and knowledge of methods by which to mitigate for hazards resulting from adverse natural or man-made conditions. The principal objective of the engineering geologist is the protection of life and property against damage caused by geologic conditions.

Engineering geologic practice is also closely related to the practice of geological engineering, geotechnical engineering, soils engineering, environmental geology and economic geology. If there is a difference in the content of the disciplines described, it mainly lies in the training or experience of the practitioner.

History

Although the science of geology has been around since the 18th century, at least in its modern form, the science and practice of engineering geology didn't begin as a recognized discipline until the late 19th and early 20th centuries. The first book entitled

Engineering Geology was published in 1880 by William Penning. In the early 20th century Charles Berkey, an American trained geologist who was considered the first American engineering geologist, worked on a number of water supply projects for New York City, then later worked on the Hoover dam and a multitude of other engineering projects. The first American engineering geology text book was written in 1914 by Ries and Watson. In 1925, Karl Terzaghi, an Austrian trained engineer and geologist, published the first text in Soil Mechanics (in German). Terzaghi is known as the father of soil mechanics, but also had great interest in geology; Terzaghi considered soil mechanics to be a sub-discipline of engineering geology. In 1929, Terzaghi, along with Redlich and Kampe, published their own Engineering Geology text (also in German).

The need for geologist on engineering works gained world wide attention in 1928 with the failure of the St. Francis dam in California and the loss of 426 lives. More engineering failures which occurred the following years also prompted the requirement for engineering geologists to work on large engineering projects.

In 1951, one of the earliest definitions of the "Engineering geologist" or "Professional Engineering Geologist" was provided by the Executive Committee of the Division on Engineering Geology of the Geological Society of America.

The Practice

One of the most important roles of the engineering geologist is the interpretation of landforms and earth processes to identify potential geologic and related man-made hazards that may impact civil structures and human development. Nearly all engineering geologists are initially trained and educated in geology, primarily during their undergraduate education. This background in geology provides the engineering geologist with an understanding of how the earth works, which is crucial in mitigating for earth related hazards. Most engineering geologists also have graduate degrees where they have gained specialized education and training in soil mechanics, rock mechanics, geotechnics, groundwater, hydrology, and civil design. These two aspects of the engineering geologists' education provides them with a unique ability to understand and mitigate for hazards associated with earth-structure interactions.

Scope of Studies

Engineering geologic studies may be performed:

- for residential, commercial and industrial developments;
- for governmental and military installations;
- for public works such as a power plant, wind turbine, transmission line, sewage treatment plant, water treatment plant, pipeline (aqueduct, sewer, outfall), tunnel, trenchless construction, canal, dam, reservoir, building, railroad, transit, highway, bridge, seismic retrofit, airport and park;
- for mine and quarry excavations, mine tailing dam, mine reclamation and mine tunneling;

- for wetland and habitat restoration programs;
- for coastal engineering, sand replenishment, bluff or sea cliff stability, harbor, pier and waterfront development;
- for offshore outfall, drilling platform and sub-sea pipeline, sub-sea cable; and
- for other types of facilities.

Geohazards and adverse geo-conditions

Typical geologic hazards or other adverse conditions evaluated and mitigated by an engineering geologist include:

- fault rupture on seismically active faults ;
- seismic and earthquake hazards (ground shaking, liquefaction, lurching, lateral spreading, tsunami and seiche events);
- landslide, mudflow, rockfall, debris flow, and avalanche hazards ;
- unstable slopes and slope stability;
- erosion;
- slaking and heave of geologic formations;
- ground subsidence (such as due to ground water withdrawal, sinkhole collapse, cave collapse, decomposition of organic soils, and tectonic movement);
- volcanic hazards (volcanic eruptions, hot springs, pyroclastic flows, debris flow, debris avalanche, gas emissions, volcanic earthquakes);
- non-rippable or marginally rippable rock requiring heavy ripping or blasting;
- weak and collapsible soils, foundation bearing failures;
- shallow ground water/seepage; and
- other types of geologic constraints.

An engineering geologist or geophysicist may be called upon to evaluate the excavatability (i.e. rippability) of earth (rock) materials to assess the need for pre-blasting during earthwork construction, as well as associated impacts due to vibration during blasting on projects.

Soil and Rock Mechanics

Soil mechanics is a discipline that applies principles of engineering mechanics, e.g. kinematics, dynamics, fluid mechanics, and mechanics of material, to predict the mechanical behavior of soils. Rock mechanics is the theoretical and applied science of the mechanical behaviour of rock and rock masses; it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment. The fundamental processes are all related to the behaviour of porous media. Together, soil and rock mechanics are the basis for solving many engineering geologic problems.

Methods and reporting

The methods used by engineering geologists in their studies include

- geologic field mapping of geologic structures, geologic formations, soil units and hazards;
- the review of geologic literature, geologic maps, geotechnical reports, engineering plans, environmental reports, stereoscopic aerial photographs, remote sensing data, Global Positioning System (GPS) data, topographic maps and satellite imagery;
- the excavation, sampling and logging of earth/rock materials in drilled borings, backhoe test pits and trenches, fault trenching, and bulldozer pits;
- geophysical surveys (such as seismic refraction traverses, resistivity surveys, ground penetrating radar (GPR) surveys, magnetometer surveys, electromagnetic surveys, high-resolution sub-bottom profiling, and other geophysical methods);
- deformation monitoring as the systematic measurement and tracking of the alteration in the shape or dimensions of an object as a result of the application of stress to it manually or with an automatic deformation monitoring system; and
- other methods.

The field work is typically culminated in analysis of the data and the preparation of an engineering geologic report, geotechnical report, fault hazard or seismic hazard report, geophysical report, ground water resource report or hydrogeologic report. The engineering geologic report is often prepared in conjunction with a geotechnical report, but commonly provide geotechnical analysis and design recommendations independent of a geotechnical report. An engineering geologic report describes the objectives, methodology, references cited, tests performed, findings and recommendations for development. Engineering geologists also provide geologic data on topograpic maps, aerial photographs, geologic maps, Geographic Information System (GIS) maps, or other map bases.

Chapter 4

Levee Breach

A levee failure during the Great Mississippi Flood of 1927.

A breach in a dike during the North Sea flood of 1953.

A **levee breach** or **levee failure** (the word dike or dyke can also be used instead of levee) is a situation where a levee fails and the water that was retained by that levee is allowed to flood the land behind the levee.

Causes of failure

Man-made levees can fail in a number of ways. The most frequent (and dangerous) form of levee failure is a *breach*. A *levee breach* is when part of the levee actually breaks away, leaving a large opening for water to flood the land protected by the levee.

Subsurface erosion

A breach can be a sudden or gradual failure that is caused either by surface erosion or by a subsurface failure of the levee. Levee breaches are often accompanied by levee boils, or sand boils. A sand boil occurs when the upward pressure of water flowing through soil pores under the levee (underseepage) exceeds the downward pressure from the weight of the soil above it. The underseepage resurfaces on the landside, in the form of a volcano-like cone of sand. Boils signal a condition of incipient instability which may lead to erosion of the levee toe or foundation or result in sinking of the levee into the liquefied foundation below. A sand boil is more threatening when a form of internal erosion called piping occurs. Complete breach of the levee may quickly follow.

Erosion and damage

Surface erosion of the surface of a levee is usually caused by the action of wind and water (waves but also normal flow). Erosion can be worsened by pre-existing or new damage to a levee. Areas with no surface protection are more prone to erosion. A levee grazed by certain types of animals, like sheep, can show trails used by the animals where grass does not grow.

Trees in levees are a special risk. A tree can become unstable after the soil of the levee has become saturated with water. When the tree falls the root system will likely take a chunk of the saturated soil out of the levee. This shallow hole can quickly erode and result in a breach. If the tree falls in the water and floats away it can damage the levee further downstream. Floating trees near levees should be quickly removed by the agency responsible for the maintenance of the levee.

Other forms of damage can be caused by ships or other (large) floating objects or from objects in the levee, like traffic signs or fences that are damaged or completely removed by wind or water. Barbed wire fences can collect large amounts of floating plant material, resulting in a large amount of drag from the water. Whole fences can be dragged away by the water.

Overtopping

Sometimes levees are said to fail when water *overtops* the crest of the levee. *Levee overtopping* can be caused when flood waters simply exceed the lowest crest of the levee system or if high winds begin to generate significant swells (a storm surge) in the ocean or river water to bring waves crashing over the levee. Overtopping can lead to significant landside erosion of the levee or even be the mechanism for complete breach. Often levees are armored or reinforced with rocks or concrete to prevent erosion and failure.

A kolk lake in the Netherlands

Kolk lakes

After a levee breach a kolk lake can often be seen. This is a crater-like depression just behind the breach where soil and other material has been violently removed by the rushing water. After a breach a kolk lake will remain when the water level recedes.

Intentional breaches

In some cases levees are breached intentionally. This can be done to protect other areas or to give back land to nature. In most cases an intentional breach is not without discussion since valuable land is given up. During the Great Mississippi Flood of 1927 a levee was blown up with dynamite to prevent the flooding of New Orleans.

Taking land from the cycle of flooding by putting a dike around it prevents it from being raised by silt left behind after a flooding. At the same time the drained soil consolidates and peat decomposes leading to land subsidence. In this way the difference between the water level on one side and land level on the other side of the dike grew. In some areas reclaimed land is given back to nature by breaching and removing dikes to allow flooding to occur (again). This restores the natural environment in the area. This happened in the Glory River in Iraq

Examples of levee breaches

New Orleans

The words *levee* and *levee breach* were brought heavily into the public consciousness after the levee failures in metro New Orleans on August 29, 2005 when Hurricane Katrina passed east of the city. Levees breached in over 50 different places submerging 80 percent of the city. Most levees failed due to water overtopping them but some failed when water passed underneath the levee foundations causing the levee wall to shift and resulting in catastrophic sudden breaching. The sudden breaching released highly pressured water that moved houses off their foundations and tossed cars into trees. This happened in the Ninth Ward when the Industrial Canal breached and also in the Lakeview neighborhood when the 17th Street Canal breached. Effects of breached levees are discussed further in the article 2005 levee failures in Greater New Orleans, which cites a death toll of 1,464. In New Orleans, the United States Army Corps of Engineers is the Federal agency responsible for levee design and construction as defined in the Flood Control Act of 1965 and subject to local participation requirements, some of which were later waived. Fault has been aimed at the Corps of Engineers, their local contractors, and local levee boards.

North Sea

The St. Elizabeth's flood of 1421 was caused by a surge of seawater being forced upriver during a storm, overflowing the river dikes and submerging approximately 300 square kilometres (100 sq mi) of land in the Netherlands. Estimates of people having died range from 2,000 to 10,000. Parts of the submerged lands have still not been reclaimed resulting in the Biesbosch wetlands.

During the North Sea flood of 1953, in the night of 31 January – 1 February 1953, many dikes in the provinces of Zeeland, Zuid-Holland and Noord-Brabant in the Netherlands were unable to withstand the combination of spring tide and a northwesterly storm. The resulting flood killed 1,835 people. A further 307 people were killed by dike breaches in the United Kingdom, in the counties of Lincolnshire, Norfolk, Suffolk and Essex. In the Netherlands these flood was a main reason for the construction of the Delta Works, probably the most innovative and extensive levee system in the world.

Other breaches

- 1421 - The St. Elizabeth's flood of 1421 in the Netherlands was caused when dikes were breached in a number of places during a heavy storm near the North Sea coast and the lower lying polder land was flooded. A number of villages were swallowed by the flood and were lost, causing between 2,000 and 10,000 casualties.
- 1570 - The All Saints' Flood caused dike breaches on the west coast of the Netherlands. The total number of dead, including in foreign countries, must have been above 20,000, but exact data is not available. Tens of thousands of people

became homeless. Livestock was lost in huge numbers. Winter stocks of food and fodder were destroyed.

- 1651 - During the St. Peter's Flood the city of Amsterdam was flooded after several breaches of the dikes, the coasts of Netherlands and Northern Germany were heavily battered.
- 1686 - The St. Martin's flood flooded large parts of the province of Groningen in the Netherlands. 1558 people, 1387 horses and 7861 cows died. 631 houses were swept away and 616 houses damaged.
- 1703 - The Great Storm of 1703 caused havoc between Wales and Friesland, it was the most severe storm or natural disaster ever recorded in the southern part of Great Britain.. Several dikes were breached in the Netherlands. Between 8,000 - 15,000 lives were lost overall.
- 1717 - The Christmas flood of 1717 was the result of a northwesterly storm, which hit the coast area of the Netherlands, Germany and Scandinavia on Christmas night of 1717. In total, approximately 14,000 people drowned. It was the last large flood in the north of the Netherlands.
- 1809 - When De Biesbosch in the Netherlands froze ice dams caused a rapid rise in waterlevels in the Meuse, Waal and Merwede, which resulted in dike breaches.
- 1820 - The Alblasserwaard in the Netherlands flooded after a dike breach
- 1825 - Parts of Groningen, Friesland and Overijssel in the Netherlands were flooded after dike breaches
- 1855 - Large parts of the central Netherlands were flooded after the Lower Rhine was dammed by ice and dikes were breached
- 1916 - A storm surge on the Zuiderzee coincided with a large volume of water flowing down the Rhine and Meuse rivers causing dozens of dike breaches
- 1927 - The Great Mississippi Flood of 1927 occurred when the Mississippi River breached levees and flooded 27,000 square miles (70,000 km^2), killing 246 people in seven states and displacing 700,000 people.
- September 1928: Storm surge from the Okeechobee Hurricane breaches levees surrounding Lake Okeechobee, killing an estimated 2500 people.
- Dec 24, 1955 - Just after midnight, a levee on the west bank of the Feather River collapsed just south of Yuba City, Ca., resulting in the drowning of 38 residents.
- Jan 3, 1976 - A dike failed on the Vliet, a tributuary of the Rupel in Belgium. The village of Ruisbroek was flooded to a depth of 3m and over 2000 people had to be evacuated. This disaster prompted the drafting of Belgium's Sigma Plan as a counterpart to the Dutch Delta Plan.
- Feb 20, 1986 - A levee on the south bank of the Yuba River collapsed at the northern Sacramento Valley community of Linda, California in Yuba County, inundating 36 square miles (93 km^2) and destroying 600 homes.
- Jan 31, 1995 - 250,000 people were evacuated from central parts of the Netherlands after river dikes had become dangerously unstable. The dikes were not breached after intensive works to stabilize the embankments, aided by military engineers.
- Jan 2, 1997 - A levee on the west bank of the Feather River collapsed at the northern Sacramento Valley community of Arboga, California in Yuba County,

killing three people. More than 100,000 people in Yuba and Sutter counties were evacuated.

- 26 Aug 2003 - A dike near Wilnis in the Netherlands failed and flooded that town due to the dike not having enough weight to withstand the water pressure of the canal after a long drought. 1,500 inhabitants were evacuated with no loss of life.
- 3 June 2004 - Jones Tract, an inland island that is protected by a series of levees located in the Sacramento-San Joaquin Delta, failed. Though the exact cause of the levee failure is not known, the breach in the levee allowed water from the Middle River to flood the island.
- January 5, 2008 - A levee in Fernley, Nevada burst, flooding portions of the town and forcing the evacuations of 3,500 residents.
- September 14, 2008 - a levee in Munster, Indiana broke on the Little Calumet River resulting in flooding in most of Munster.
- August 8, 2009 - Levees fail in Southern Taiwan due to Typhoon Morakot causing widespread flooding in many regions.
- February 26, 2010 - Levees were submerged by wind and a huge tide in Vendée, in Western France because of the Xynthia storm.

Chapter 5

Infill

Kaiser Medical Center in Richmond, California has infilled its employee parking to expand the hospital's emergency services department.

Infill in its broadest meaning is material that fills in an otherwise unoccupied space. The term is commonly used in association with construction techniques such as wattle and daub, and civil engineering activities such as land reclamation.

Construction

When a building is constructed in timber framing, the spaces are filled with non-structural material that is known as infill. The earliest type of infill was wattle and daub. Other materials used for the purpose have been lath and plaster, and brickwork (when it is known as nogging). The infill may be covered by other materials, including plaster, weatherboarding or tiles.

Urban planning

Urban infill

Example of an urban infill site

In the urban planning and development industries, infill is the use of land within a built-up area for further construction, especially as part of a community redevelopment or growth management program or as part of smart growth. It focuses on the reuse and repositioning of obsolete or underutilized buildings and sites. This type of development is essential to renewing blighted neighborhoods and knitting them back together with more prosperous communities. Redevelopment is development that occurs on previously developed land. Infill buildings are constructed on vacant or underutilized property or between existing buildings.

Challenges to urban infill

Although infill is an appealing tool for community redevelopment and growth management, it is often far more costly for developers to develop land within the city than it is to develop on the periphery, in suburban greenfield land. Costs for developers include acquiring land, removing existing structures, and testing for and cleaning up any environmental contamination.

Scholars have argued that infill development is more financially feasible for development when it occurs on a large plot of land (several acres). Large scale development benefits from what economists call economies of scale, and reduces the surrounding negative influences of neighborhood blight, crime, or poor schools. However, large scale infill development is often difficult in a blighted neighborhood for several reasons. These include the difficulties in acquiring land and in gaining community support.

Amassing land is one challenge that infill development poses that greenfield development does not. Neighborhoods that are targets for infill often have parcels of blighted land scattered among places of residence. Developers must be persistent in order to amass land parcel by parcel, and often find resistance from landowners in the target area. One way to approach this problem is for city management to use eminent domain to claim land. This is often unpopular among city management, as well as among neighborhood residents. Developers must deal with regulatory barriers, visit numerous government offices for permitting, interact with city management that is frequently unwilling to use eminent domain to remove current residents, and generally engage in public-private partnerships with local government.

Developers also meet with high social goal barriers in which the local officials and residents are not interested in the same type of development. Although citizen involvement has been found to facilitate the development of brownfields, residents in blighted neighborhoods often want to convert vacant lots to parks or recreational facilities, whereas external actors seek to build apartment complexes, commercial shopping centers, or industrial sites.

Suburban infill

Suburban infill describes the development of land in existing suburban areas that was left vacant during the development of the suburb. It is one of the tenets of the New Urbanism and smart growth trends of urging densification to reduce the need for automobiles, encourage walking, and ultimately save energy. One exception to this is the practice of urban agriculture, in which land in the urban or suburban area is retained to grow food for local consumption.

The Village of Ponderosa in West Des Moines, Iowa is a good example of suburban infill. It was formerly a 9-hole golf course surrounded by suburban West Des Moines businesses and tract homes, but starting in 2006 it was redeveloped into a higher-density mixed-use community with a pedestrian friendly retail center.

Infill housing

Infill housing is the insertion of additional housing units into an already approved subdivision or neighborhood. These can be provided as additional units built on the same lot, by dividing existing homes into multiple units, or by creating new residential lots by further subdivision or lot line adjustments. Units may also be built on vacant lots.

Infill residential development does not require the subdivision of greenfield land, natural areas, or prime agricultural land. Existing infrastructure may in some cases need little expansion for utility and other services.

As with other new construction, structures built as infill may clash architecturally with older, existing buildings.

Infill, a water and aeolian process

Examples of *infills* occur in geology. The Touchet Formation of rhythmite layers located in the Northwestern United States, had intervening periods of aridity. Erosional cracks were later infilled with layers of soil material, especially from aeolian processes. The infilled sections formed vertical inclusions in the horizontally deposited layers of the Touchet Formation, and thus explaining events that intervened in time among the forty-one layers that were deposited.

Chapter 6

Shaft Construction

Shaft construction concerns the building of vertical openings such as Raises and Shafts. Shafts are vertical openings used for supplying equipment, personnel, and support systems to the horizontal tunnel where the pipeline is installed. They can be temporary or permanent, Which need large size excavations.

In this report we will addresses the different construction methods and different applications of shafts and raises, and during that we will also talk about the advantage and disadvantage of each method. In addition, we will talk about their impacts on surrounding infrastructures and environment, resource requirements, appropriate soil conditions, site layout requirements and finally we will have a rough cost estimation.

Definitions, applications, shapes

Raisings

Raisings are driven in the upward direction. They can be vertical or steeply inclined. During raising, gravity assists in drilling and mucking, thereby making the process faster and cheaper. (R. Tatia 2005)

Shafts

Shafts are vertical openings which are driven downward. Decisions about the size, shape and positioning of shafts and raisings are taken based on the purpose they are intended to serve. (R. Tatia 2005)

Usually circular shafts are preferred in almost all situations because they are very stable. Also, when strata should be built, we can use the advantages of rectangular or elliptical shafts and use their cross sectional areas. (R. Tatia 2005)

Applications

According to (R. Tatia 2005) applications of raises and shafts are listed below:

Hydro-electric projects

- surge chamber
- ventilation shaft
- elevator shaft
- pressure shaft
- cable shaft

Water supply

- access or service shaft
- ventilation
- supply riser
- uptake or down-take shaft

Waste water shafts

- drop shafts

Tunnel projects

- ventilation
- accelerators housing
- access

Raise driving techniques

One classification for the raises is based on the application of explosives, that is to say with and without explosives while driving. (R. Tatia 2005)

The line diagram below shows a classification of raising techniques: (R. Tatia 2005)

Conventional methods

- the open rising technique is used in driving short raises which are less than 10 meters.
- Compartment method

Raising by mechanical climbers: Alimak raise climber

Alimak Company introduced this technique in 1957, and even today it is often used in driving blind raises which have long lengths.

The Alimak raise climber is designed to drive raises up to 100 m long, or more. There are several kinds of climbers available: pneumatic, electric and diesel (hydraulic driven).

The following are important features of this technique:

- it makes it possible to drive very long raises, vertical or inclined, straight or curved and mostly rectangular shape.
- The raise climber can be driven into a safe position using backward guardrails.
- Because of its features for blowing air and water at the face after blasting, risks of foul gases are eliminated, and the time required for ventilation is reduced.
- An additional extension piece can be connected to the platform

Blast hole techniques

- Long hole raising
- Drop rising

"Drop rising" technique is the advanced version of the "long hole raising" technique. This technique is based on the vertical carter retreat (VCR) concept. The crater has five holes, one of the holes is at the center and the other four are at the corners. In this method (DTH) drills, drill parallel holes in the raise direction. After that holes are blasted in stages. Raises of longer lengths, up to 150 m, can be drilled using this method.

Raising by application of raise borers

This technique can be used to drive a raise between 2 levels in the ground. Using this technique, Raises have been drilled successfully even in poor ground where the soil condition is not very good. A circular shape is obtained from this technique. In this technique, the machine is set up at the top and drills a hole of 225 to 250 mm diameter, to get to the lower level. After that a large reamer bit is put on at the bottom of the drill rod and then it reams up the raise.

We can execute the reverse procedure by the machine; however, this option is not very popular.

Raise borers can drive in soft ground and hard ground, and such units are useful to drive raises and shafts up to 6 m diameter,

This method has the advantages like, faster rates, better safety for working crews and least disturbance to the rock structure.

By using this method the holes by the following properties is driven before: Shaft length, 1000 m, Diameter .6 to 6 m (R. Tatia 2005)

Shaft sinking

Applications of Shafts: (R. Tatia 2005)

Shafts are usually used for the following purposes: "

- Mining mineral deposits
- Temporary storage and treatment of sewage
- Bridge and other deep foundations
- Hydraulic lift pits
- Wells
- In conjunction with a tunnelling system or network, for the purpose of lifts, escalators, stair and ladder ways, ventilation, conveyance of liquid, carrying pipes and cable in river crossing, drainage and pumping, particularly from sub aqueous tunnels."

They also can be temporary or permanent,

(R. Tatia 2005) has classified the techniques which are used for sinking shafts:

Activities required for Shaft Sinking

we can divide the operations for sinking a shaft into three parts: (R. Tatia 2005)

1. Reaching up to the rock head
2. Sinking through the rock
3. Sinking through the abnormal difficult ground, if any, using special methods

A sinking cycle includes the following operations: (R. Tatia 2005)

- Drilling
- Blasting
- Mucking and hoisting
- Support or shaft lining
- Auxiliary operations
  - Dewatering
  - Ventilation
  - Lightning or illumination
  - Shaft centering

Drilling

We use sinkers to drill holes of 32–38 mm diameter, The length of the holes vary between 1.5 to 5 meters.

There are three types of cuts

- Wedge cut
- Step cut
- Pyramid cut

1 and 2 are common drilling that are used and in rectangular shafts. Wedge cut is used most of the time. Pyramid cut is often used in the circular ones. Step cut is adopted if water is high and the shaft is of a large cross section.

Blasting

In practice, at the bottom of shaft is usually full of water during sinking. therefore, high density, water-resistant explosives are used.

Lashing and mucking

Lashing is made for the loading of muck into a conveyance for its disposal. This activity is a time consuming activity due to Presence of water, limited space.

Support or shaft lining

There are two types of lining,

- Temporary
- Permanent

The type of water and strength of the rock and soil layer where sinking operation is done determine which option to select. Therefore, in some cases, temporary support is not adopted, while in others it becomes essential to protect the crew and equipment from any side fall.

The permanent lining can be made of bricks, concrete blocks, monolithic concrete, shotcrete and cast iron tubing.

Auxiliary operations

- Dewatering: When the shaft is reached to the water table or beyond it, water inflows inside it, to remove this water usually face or sinking pumps are used.(tatiana) Removing water can also be done by driving deep wells or well point systems around the shaft, that results in lowering the water table around the shaft.(zhou)
- Ventilation: Fresh air, supplied by a forcing fan installed at the surface, which can be provided by rigid ventilation ducts for below 6 m depth or flexible ones for more than 6 m depth.
- Illumination: A pneumatically operated light, is used to provide illumination at the working face during construction work.
- Shaft centering: Using the reference points, which are fixed before, to fix the shaft center. The shaft center is checked from time to time by the use of centering device installed at the surface.

Special methods for shaft sinking.

In the process of shaft sinking, it becomes necessary to adopt a special method if the ground through which the shaft is sunk is loose or unstable such as in sand, mud, gravel, or alluvium, or when an excessive amount of water is encountered, which cannot be dealt with by sinking pumps. In some situations, both sets of these conditions my be encountered. Listed below are special methods that can be used to deal with the situations outlined above:

1. piling system
2. cementation
3. freezing method
4. grouting
5. shotcrete

1. Piling system (Soldier pile):

These piles are driven and after installing the steel beams can be concreted. Piling method and the spaces between piles depend on the soil conditions. (Fangyi Zhou, 2006)

3. Freezing method

”Sometimes when we can’t control the groundwater by pumping, we may use freezing or grouting. This procedure consists of sinking pipes around the area to be excavated and circulating a cold brine solution through the pipes, thereby freezing a wall of soil, this process needs 2 months to complete,” . (Fangyi Zhou, 2006)

4. Grouting:

In this method we drill rows of grout holes around the shaft perimeter, then inject grout into them, but freezing is more reliable comparing to this,

5. Shotcrete:

Shotcrete is sprayed concrete can be applied immediately to freshly excavated rock

Impact on surrounding infrastructures

Shaft sinking can have the following impacts on the infrastructure and environment around it:

- blocking the streets and causing traffic in the area around it
- making noise and dust which can bother the people around the construction area
- bad effects on soil because of making vibrations in the ground while construction
- cutting some trees and clearing the area for construction site

Appropriate soil conditions

The appropriate soil condition For each method is mentioned during the construction method, and if the soil is not strong, we should use piles and temporary linings to take care of that The space between columns depends on the soil conditions and amount of ground water existing, piles can be close to each other or have the appropriate distance.

However, strong and consolidated soil is the most appropriate soil for driving shafts. (class lectures)

Site layout requirements

Tommelein (1989) defines Construction site layout and its benefits as below:

“ identifying the facilities that are temporary needed to support construction operation on a project but that do not form apart of the furnished structure: determining the size and shape of these facilities; positioning them within the boundaries of the available on-site or remote areas”

“the so called temporary facilities usually remain on site for a period ranging from a few days to several months or even years, a time period that ranges from duration of a construction activity to the duration of a major phase of the entire construction period”

“ a well-organized site facilities inventory control, cuts travel times, reduces noise and dust, prevents obstructions and interference, increases safety and security, and improves site access”

According to Fangyi Zhou (2006), considerations affecting the site layout are: Efficiently using site space to accommodate resources throughout a construction project is fundamental to success of a project. So optimizing the construction site layout using physical and computational models is of interest to many researchers. Site Layout has a great effect on project costs, therefore, models are used to simulate the different site layouts and choose the best one.

Resources required: (cost estimation for shaft, City of Edmonton,2005)

Human resources

Equipment operators, labourers and workers, foremen, supervisors

Equipments and machines

- Drill rig, compressor, excavators, explosives
- Cranes, hoists, trucks
- Welding truck

- Lumbers (laggings), liners, ribs, tie rods, support beams, tie wire
- General purpose concrete, concrete forms, concrete pump, rebars
- Water pumps
- Illumination and electrical equipment
- Communication systems
- Personal protective equipment
- Ventilation System
- Instrumentation to determine the concentration of flammable gases

Chapter 7

Shoring

Shoring is a general term used in construction to describe the process of supporting a structure in order to prevent collapse so that construction can proceed. The phrase can also be used as a noun to refer to the materials used in the process.

Buildings- It is used to support the beams and floors in a building while a column or wall is removed. In this situation vertical supports are used as a temporary replacement for the building columns or walls.

Trenches - During excavation, shoring systems provide safety for workers in a trench and speed excavation. In this case, shoring should not be confused with shielding. Shoring is designed to prevent collapse where shielding is only designed to protect workers when collapses occur. Concrete structures shoring, in this case also referred to as falsework, provides temporary support until the concrete becomes hard and achieves the desired strength to support loads.

Ships - It is used onboard when damage has been caused to a vessels integrity, and to hold leak-stopping devices in place to reduce or stop incoming water. Generally consists of timber 100 mm x 100 mm and used in conjunction with wedges, to further jam shoring in place, pad pieces to spread the load and dog's to secure it together. also used onboard is mechanical shoring as a quick, temporary solution, however it isn't favoured due to its inability to move with the vessel.

Shoring Techniques

Buildings

Raking Shore

Raking Shores consist of one or more timbers sloping between the face of the structure to be supported and the ground. The most effective support is given if the raker meets the wall at an angle of 60 to 70 degrees. A wall-plate is typically used to increase the area of support.

Foundations

Shoring is commonly used when installing the foundation of a building. A shoring system such as piles and lagging or shotcrete will support the surrounding loads until the underground levels of the building are constructed.

Trenches

Hydraulic Shoring

Hydraulic shoring is the use of hydraulic pistons that can be pumped outward until they press up against the trench walls. They are typically combined with steel plate or plywood, either being 1-1/8" thick plywood, or special heavy Finland Form (FINFORM) 7/8" thick.

Beam and Plate

Beam and Plate steel I-beams are driven into the ground and steel plates are slid in amongst them. A similar method that uses wood planks is called soldier boarding. Hydraulics tend to be faster and easier; the other methods tend to be used for longer term applications or larger excavations.

Soil Nailing

Soil nailing is a technique in which soil slopes, excavations or retaining walls are reinforced by the insertion of relatively slender elements - normally steel reinforcing bars. The bars are usually installed into a pre-drilled hole and then grouted into place or drilled and grouted simultaneously. They are usually installed untensioned at a slight downward inclination. A rigid or flexible facing (often sprayed concrete) or isolated soil nail heads may be used at the surface.

Continuous Flight Augering

Continuous Flight Augering (CFA) is a method used to create concrete piles to support soil so that excavation can take place nearby. A Continuous Flight Augering drill is used to excavate a hole and concrete is injected through a hollow shaft under pressure as the auger is extracted. This creates a continuous pile without ever leaving an open hole.

Ships

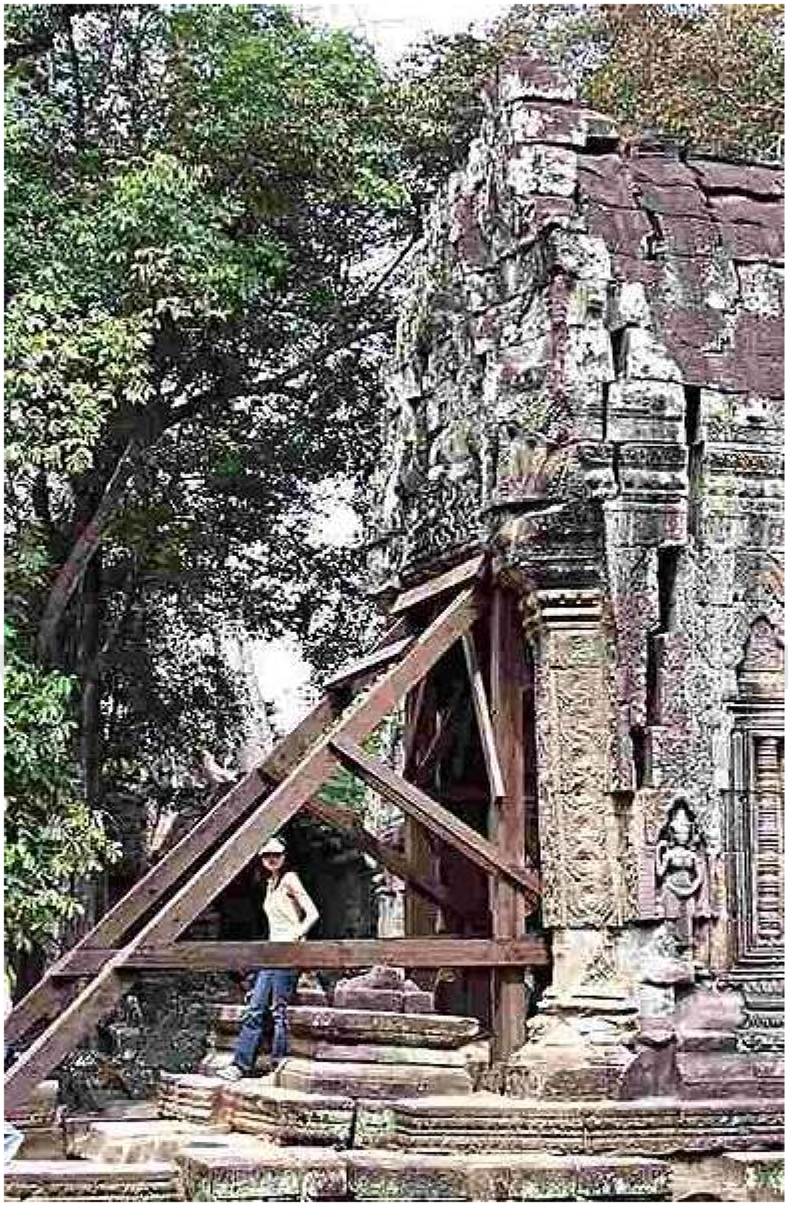
Square Shoring

This consists of a timber member jammed on a pad piece on either the deck or deck head depending on water levels in the compartment and a strong point, this is called the proud. then the is a horizontal timber cut to size to fit between this and what it is shoring up, eg a splinter box, bulkhead or door. Timber wedges are then used to tighten up the structure if necessary

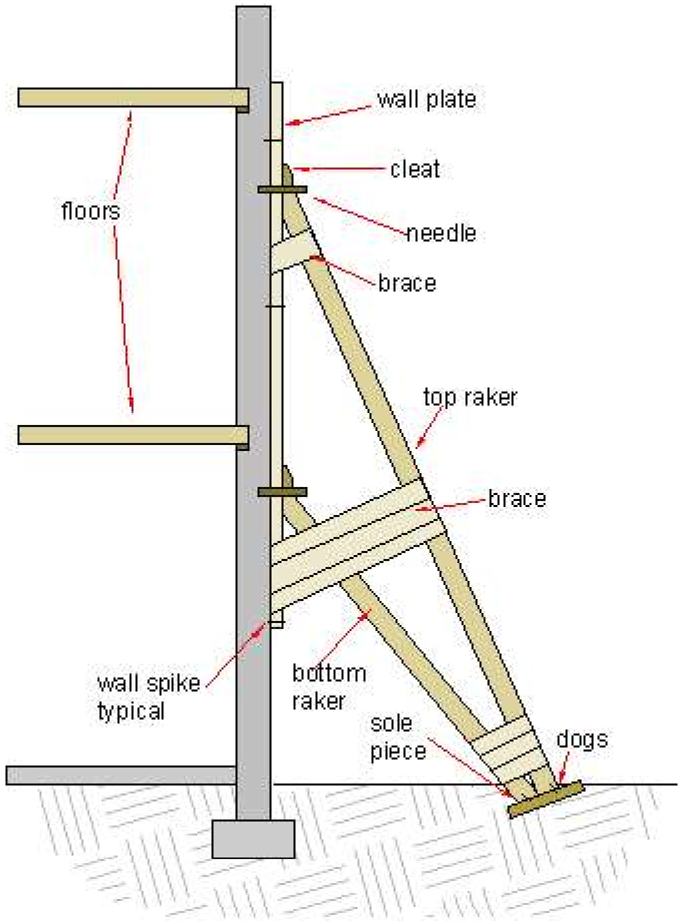
Vertical Shoring This is to support a hatch or splint box on the deck, consisting of a vertical timber between the deck and deck head, with to wedges used opposing each other to tighten it. pad pieces are used to spread the load on weak structures.

Vertical or dead shore system, typically used in formwork.

Single steel raking shore system specifically for tilt slab shoring.

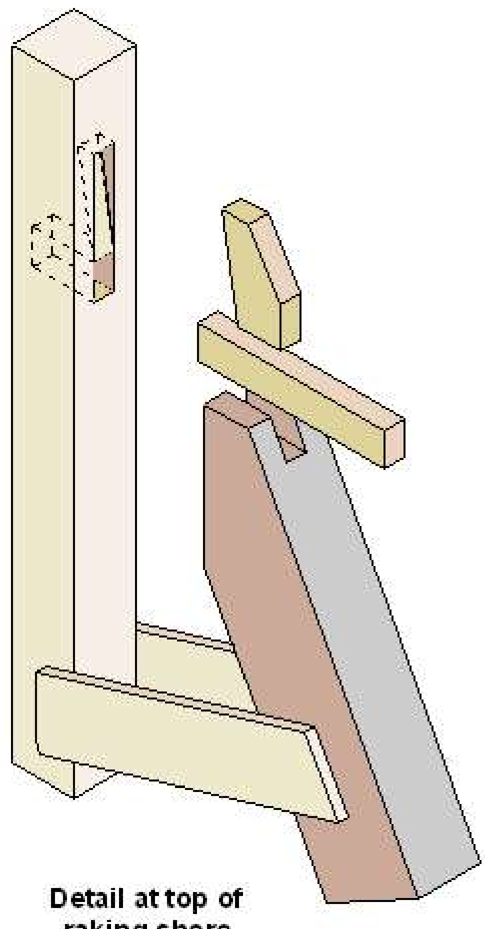


Angkor Wat complex, simple combination of timber raking and dead shores.

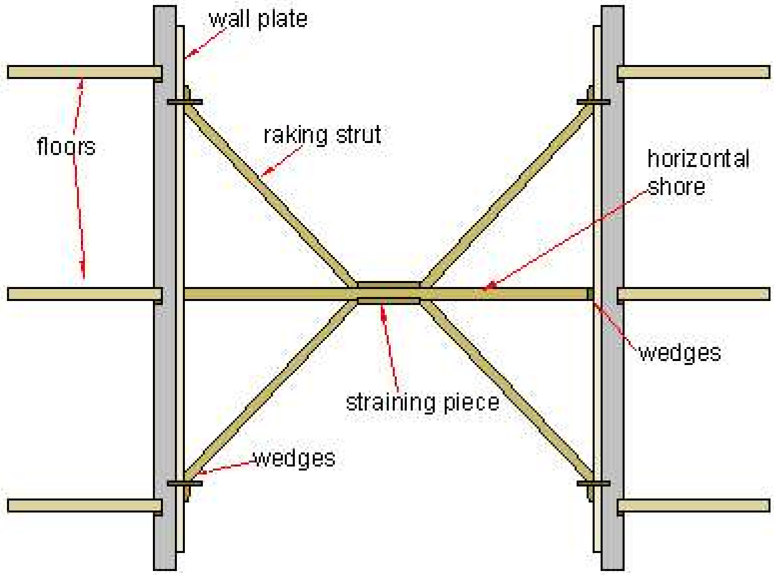


A Double Raking Timber Shore

Sketch of a timber double raking shore. Projected centre lines of floors and shores meet.

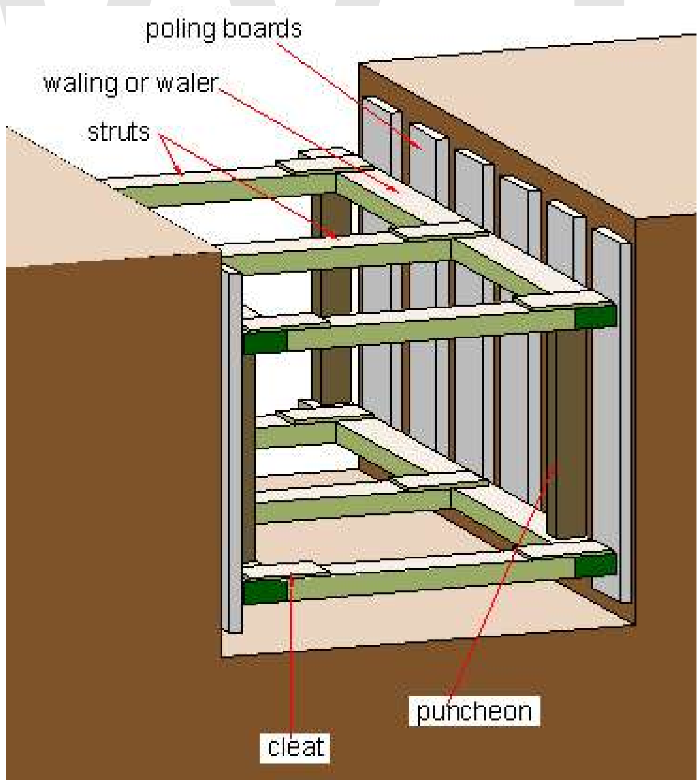


Carpentry detail of the joint at the top of a timber raking shore.

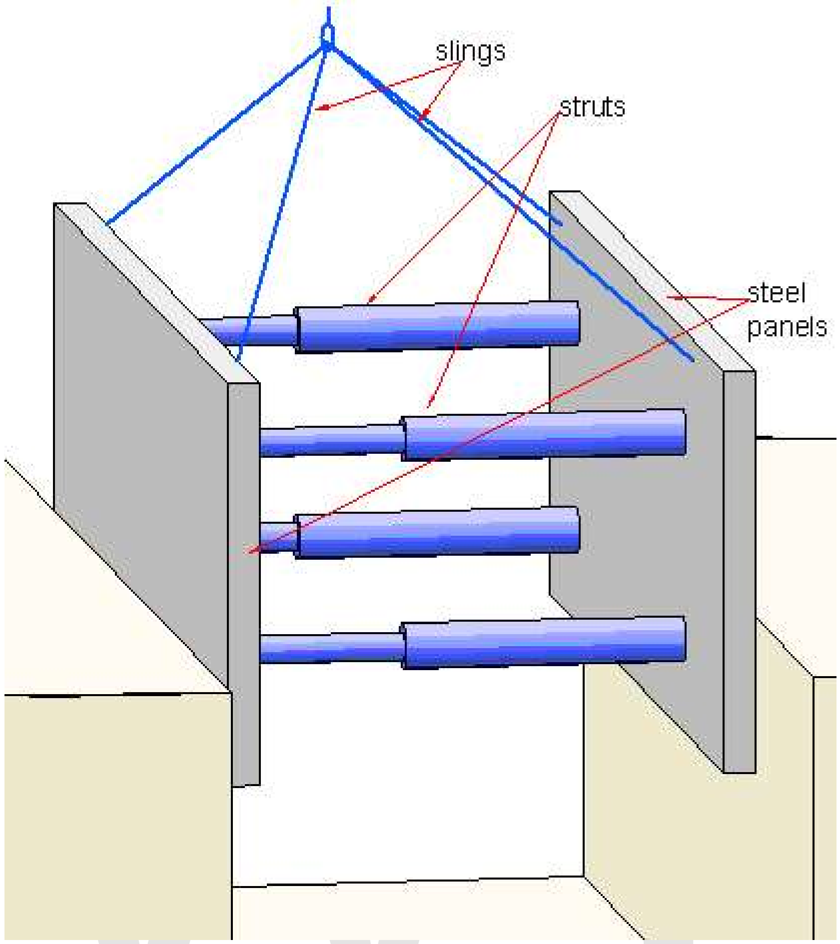


Part Elevation Through Two Buildings
With A Single Flying Timber Shore

Sketch of a timber single flying shore between adjacent buildings.



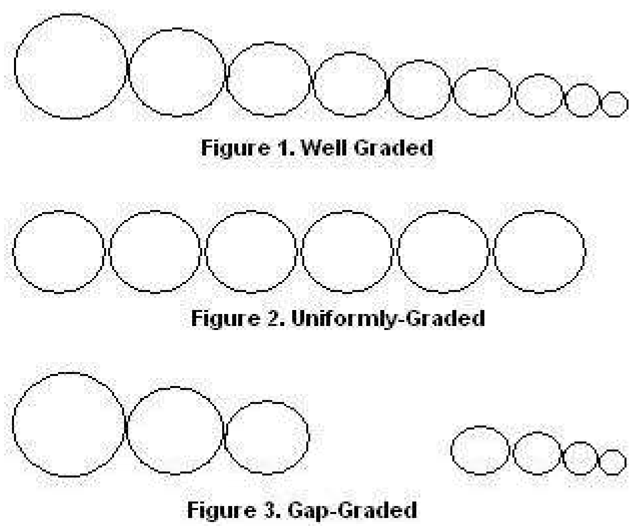
Traditional trench shoring or Timbering.



Schematic sketch of a modern steel trench shore being lowered into a trench.

Chapter 8

Soil Gradation



Soil Gradation Categories

Soil gradation is a classification of a coarse-grained soil that ranks the soil based on the different particle sizes contained in the soil. Soil gradation is an important aspect of geotechnical engineering and is an indicator of other engineering properties such as compressibility, shear strength, and hydraulic conductivity. In a design, the gradation of the in situ or on site soil often controls the design and ground water drainage of the site. A poorly graded soil will have better drainage than a well graded soil.

Soil is graded as either well graded or poorly graded. Poorly graded soils are further divided into uniformly-graded or gap-graded soils.

Soil gradation is determined by analyzing the results of a sieve analysis or a hydrometer analysis.

The process for grading a soil is in accordance with either the Unified Soil Classification System or the AASHTO Soil Classification System. Gradation of a soil is determined by reading the grain size distribution curve produced from the results of laboratory tests on the soil. Gradation of a soil can also be determined by calculating the coefficient of uniformity, C_u, and the coefficient of curvature, C_c, of the soil and comparing the calculated values with published gradation limits.

Soil Gradations

Soil gradation is a classification of the particle size distribution of a soil. Coarse-grained soils, mainly gravels or sands, are graded as either well graded or poorly graded. Poorly graded soils are further divided into uniformly-graded or gap-graded soils. Fine-grained soils, mainly silts and clays, are classified according to their Atterberg limits.

Well Graded

A *well graded* soil is a soil that contains particles of a wide range of sizes and has a good representation of all sizes from the No. 4 to No. 200 sieves. A well graded gravel is classified as GW while a well graded sand is classified as SW.

Poorly Graded

A *poorly graded* soil is a soil that does not have a good representation of all sizes of particles from the No. 4 to No. 200 sieve. Poorly graded soils are either uniformly graded or gap-graded. A poorly graded gravel is classified as GP while a poorly graded sand is classified as SP. Poorly graded soils are more susceptible to soil liquefaction than well graded soils.

A *uniformly graded* soil is a soil that has most of its particles at about the same size. An example of a uniformly graded soil is one in which only sand of the No. 20 size is present.

A *gap-graded* soil is a soil that has an excess or deficiency of certain particle sizes or a soil that has at least one particle size missing. An example of a gap-graded soil is one in which sand of the No. 10 and No. 40 sizes are missing, and all the other sizes are present.

Process of Grading a Soil

The process of grading a soil is in accordance with either the Unified Soil Classification System or the AASHTO Soil Classification System. The steps in grading a soil are data collection, calculating coefficients of uniformity and curvature, and grading the soil based on the grading criteria given in the used soil classification system.

Data Collection

Soil gradation is determined by analyzing the results of a sieve analysis or a hydrometer analysis.

In a sieve analysis, a coarse-grained soil sample is shaken through a series of woven-wire square-mesh sieves. Each sieve has successively smaller openings so particles larger than the size of each sieve are retained on the sieve. The percentage of each soil size is measured by weighing the amount retained on each sieve and comparing the weight to the total weight of the sample. The results of a sieve analysis are plotted as a grain size distribution curve, which is then analyzed to determine the soil gradation of the particular soil.

In a hydrometer analysis, a fine-grained soil sample is left to settle in a viscous fluid. This method is used based on Stoke's Law which relates terminal velocity of fall of a particle in a viscous fluid to the grain diameter and density of the grain in suspension. Grain diameter is calculated from a known distance and time of the fall of the particle. This is used to classify fine-grained soils.

Calculating the Coefficients of Uniformity and Curvature

Calculating the coefficients of uniformity and curvature requires grain diameters. The grain diameter can be found for each percent of the soil passing a particular sieve. This means that if 40% of the sample is retained on the No. 20 sieve then there is 60% passing the No. 20 sieve.

The *coefficient of uniformity*, C_u is a crude shape parameter and is calculated using the following equation:

$$C_u = \frac{D_{60}}{D_{10}}$$

where D_{60} is the grain diameter at 60% passing, and D_{10} is the grain diameter at 10% passing

The *coefficient of curvature*, C_c is a shape parameter and is calculated using the following equation:

$$C_c = \frac{(D_{30})^2}{D_{10} * D_{60}}$$

where D_{60} is the grain diameter at 60% passing, D_{30} is the grain diameter at 30% passing, and D_{10} is the grain diameter at 10% passing

Once the coefficient of uniformity and the coefficient of curvature have been calculated, they must be compared to published gradation criteria.

Criteria for Grading Soils

The following criteria are in accordance with the Unified Soil Classification System:

For a gravel to be classified as well graded, the following criteria must be met:

$C_u > 4$ & $1 < C_c < 3$

If both of these criteria are met, the gravel is classified as well graded or GW. If both of these criteria are not met, the gravel is classified as poorly graded or GP.

For a sand to be classified as well graded, the followinng criteria must be met:

$C_u > 6$ & $1 < C_c < 3$

If both of these criteria are met, the sand is classified as well graded or SW. If both of these criteria are not met, the sand is classified as poorly graded or SP.

Importance

Soil gradation is very important to geotechnical engineering. It is an indicator of other engineering properties such as compressibility, shear strength, and hydraulic conductivity.

In a design, the gradation of the in situ or on site soil often controls the design and ground water drainage of the site. A poorly graded soil will have better drainage than a well graded soil because there are more void spaces in a poorly graded soil.

When a fill material is being selected for a project such as a highway embankment or earthen dam, the soil gradation is considered. A well graded soil is able to be compacted more than a poorly graded soil. These types of projects may also have gradation requirements that must be met before the soil to be used is accepted.

When options for ground remediation techniques are being selected, the soil gradation is a controlling factor.

Chapter 9

Suction Excavator

A **suction excavator** or **vacuum excavator** is a construction vehicle that removes earth from a hole on land, or removes heavy debris on land, from various places, by powerful suction through a wide suction pipe which is up to a foot or so diameter. The suction inlet air speed may be up to 100 meters/second = over 200 mph.

The suction nozzle may have two handles for a man to hold it by; those handles may be on a collar which can be rotated to uncover suction-release openings (with grilles over) to release the suction to make the suction nozzle drop anything which it has picked up and is too big to go up the tube.

The end of the tube may be toothed. This helps to cut earth when use for excavating; but when it is used to suck up loose debris and litter, some types of debris items may snag on the teeth.

The earth to be sucked out may be loosened first with a compressed-air lance, or a powerful water jet.

Its construction is somewhat like a gully emptier but with a wider suction hose and a more powerful suction.

Excavating with a suction excavator may called "vacuum excavation", or "hydro excavation" if a water jet is used.

History

RSP Gmbh have been making suction excavators and stationary suction units since 1993, but gully emptiers and the old type of suction street cleaner vehicle that could only pick up loose debris have been around for much longer.

Since 1998, the MTS Mobile Tiefbau Saugsysteme GmbH is making a new type of suction excavator. It is said to have a new designed air flow principle, and thus a considerably improved suction performance.

Design and operation

RSP Gmbh

RSP Gmbh in Germany make or made these models:

model	length	fan capacity	suction negative pressure	maximum suction depth	maximum suction span	spoil tank volume	specifications of carrying truck				info link
							power	axles	wheelbase	weight	
ESE 18/7	7 m	6.94 – 8.88 m³/s	0.1 - 0.17 bar	15 m	70 m	4 cu.m.	280 hp	≥ 2	4.2 m = 13 ft 10 in	18 tonnes	
ESE 19/5	8 m	5 - 6.94 m³/s	0.1 - 0.17 bar	11 m	50 m	5 cu.m.	310 hp	≥ 2	4.5 m = 14 ft 10 in	19 tonnes	
ESE 26/7	8.8 m	5 - 6.94 m³/s	0.1 - 0.17 bar	11 m	50 m	7 cu.m.	310 hp	≥ 3	4.2 m = 13 ft 10 in	28 tonnes	
ESE 32/7	9.8 m	8.8888 m³/s	0.3 bar	16 m	100 m	7 cu.m.	400 hp	≥ 4	4.2 m = 13 ft 10 in	32 tonnes	

The suction unit is roughly rectangular-block-shaped, about 2.5 meters wide and 3.6 meters high, and is usually mounted and used on the back of a truck, which must have power takeoffs to run the suction unit's air impeller and hydraulics.

When it is emptying its load out, the spoil tank lid (with the hose connection) hinges off to the right, then the spoil tank (with the filters) tips about 90º over to the left to tip its load out.

In the ESE 32/7:

- The suction pipe's internal diameter is 25 cm = 9.8 inches
- The fan produces a maximum pressure reduction of about 30,000 pascals = about 0.3 atmosphere or 4.5 pounds/square inch. Across a circular suction opening 9.8 inches diameter that would give an entry air speed of about 400 mph and a maximum suction power of about 340 pounds = about 3 hundredweight. It can suck up objects up to 25 cm or 9.8 inches across of weight up to 30 kilograms = 66 pounds.
- It is described as able to suck up "earth, stones, vegetable waste, sand, mud, water, pebbles, rubble, asbestos, railway-type ballast"
- Its suction pipe has a detachable extension nozzle narrowing from 10 inches to 4 inches internal diameter, with handles on a rotatable panel to open or close side vents to let the operator let it drop overlarge objects which it has picked up.
- Its expected spoil extraction rates are roughly, in cubic meters per hour:

material	cu.m./hour	time for 1 cu.m.
heavy soil with buried cables and pipes	1.6666	36 mins
dry heavy soil	2.5	24 mins
wet heavy soil or clay	3	20 mins

moderately heavy soil with buried cables and pipes	4	15 mins
muddy soil, gravel, crushed rock	6	10 mins
sandy soil	10	6 mins
water	30	2 mins
heavy soil with buried cables and pipes excavated by hand	*0.25*	*4 hours*

4 views of a suction excavator truck

Cleaning out a sewer manhole

Cleaning a riverbank

Removing building demolition or alteration debris

Trench digging

Removing builder's rubble from a confined area

Removing a ditched truck's load to make the truck light enough to be righted

Emptying a suction excavator's spoil hold into a dump truck

Internal diagram (in French)

Extension nozzle, narrowing from 10 inches to 4 inches internal diameter

Sucking down a hole being dug to work on gas mains, Deansgate, Manchester. The man on the near right is pneumatic drilling.

Work in confined space, Deansgate, same site. The man on the right is loosening earth with a compressed air lance.

Work in confined space, Deansgate, same site

View across work site, Deansgate, same site

Suction excavator, close-up of pipe end, stowed away

Back view of suction excavator with kit stowed away

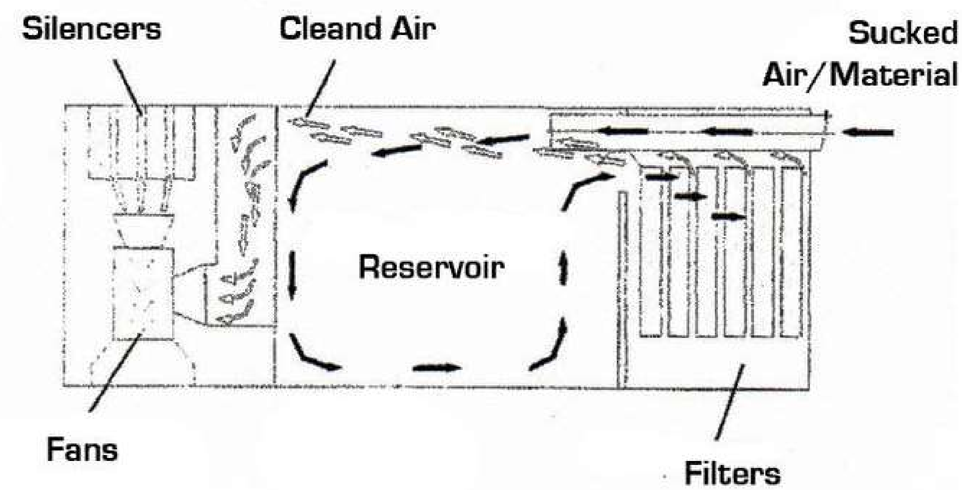
MTS Mobile Tiefbau Saugsysteme GmbH

MTS GmbH in Germersheim, Germany is making since 1998 these types of suction excavators:

Model	Fan	Air movement	Suction pressure	Spoil capacity	Max. suction depth	Max. suction distance	Suction hose diameter	Info link	Notes
Suction Box SBO				1-2m³			125-200mm = 4.932 - 7.87 inches		Can be carried by excavators etc. In 22, 32, 42 kW versions.
MINI-VAC	Single turbine	6,944 m³/sec	0.1974 bar	1,5-2m³	5m	25m	200mm = 7.87 inches		buildup on 7.5 ton truck, compact for difficult-to-reach sites
DINO 2-5	Single or double turbine	6.944 – 10 m³/sec	0.335 bar	4m³ - 12m³	20m+	100m+	250mm= 9.84 inches		with telescopic boom or hydraulic boom
MEGA-VAC	Quadruple turbine	10 m³/sec	0.493 bar	9m³	30m+	200m	250mm = 9.84 inches		big for big jobs

With the MEGA-VAC the suction power across a 9.84-inch-wide hose entry would be about half a ton.

The MTS suction excavators are said to have a much easier air routing that leads to a more open spoil-hold design and much better suction performance.



Working principle of a MTS suction excavator

MTS Suction Excavator Mini Vac

MTS suction excavator DINO Tridem

MTS suction excavator Dino 4 in yellow

MTS suction excavator Dino 5 in green

MTS suction excavator Dino on Tridem chassis

MTS suction excavator at work at urban site

MTS Suction excavator while tipping

Saugmaster

Saugmaster make a model similar to the ESE 32/7; it can suck 8 cu.m./second of air, and its suction tube is 9 inches = 23 cm wide inside.

Ditch Witch

The USA firm Ditch Witch makes 4 models of suction excavators: FX20, FX25, FX30, FX60; the number is its approximate horsepower. It is mounted on a semitrailer. It has its own engine (petrol for FX20, the others diesel). Its spoil tank is cylindrical with somewhat rounded ends. Its suction hose is 3 inches diameter inside (but the FX60 can take 4-inch-diameter suction hose). Its spoil tank can be supplied various sizes.

Airex

Airex GB Ltd in the UK make two current models of vacuum excavator: AX-68 and AX-180. Both systems are mounted on the back of rigid 7.5-ton trucks, designed for use in inner-city streets. The smaller design of these trucks gives less impact on their surroundings. The AX-68 uses a 4-inch hose but the AX-180 uses an 8-inch hose which can removing a tonne of earth in six minutes.

Vac-Tron Equipment, LLC

Vac-Tron Equipment, LLC in the U.S. makes more than 50 models of gasoline and diesel vacuum excavators. They offer trailer and skid mounted options, and gasoline and diesel. Spoil tanks come in various sizes and configurations. Low profile increases maneuverability and can be towed by as small as a half-ton pickup truck.

Uses

Suction excavators are useful to remove earth from around existing buried services or tree roots with much less risk of damaging them than using a conventional excavator with a metal scoop.

This type of excavation is held to be a safe and efficient form of excavation. However it is totally unsuitable for archaeological excavation. Using a powerful vacuum and high pressure water, precise holes, trenches and tunnels can be cut to the required size and proportion. Because compressed air or water is used to loosen the earth, the risk of damaging underground utilities is less and contractors can safely find and expose them. Often excavation reveals unknown utilities, saving lives, money and time.

It is also referred to as "daylighting", as the underground utilities are exposed to daylight during the process.

This type of excavating is quickly becoming recognized as a best practice when working in areas with underground utility congestion and frozen ground. Hydro excavation lessens the risk of damaging utilities, which may often be inaccurately mapped and located and marked on the surface.

A suction excavator is useful in bulk excavation in confined areas, where its suction hose can reach in over or through barriers, e.g. digging a swimming pool in a courtyard.

It can be used on railways (perhaps mounted on a railroad car base) to suck old track ballast off the track when re-ballasting the track.

It can be used as a very heavy-duty vacuum cleaner to pick up miscellaneous debris, e, g, rubble, or big accumulations of fallen leaves or litter.

It can suck up liquids, e.g. water from a hollow.

The National Grid (UK) (UK electricity suppliers) has ordered 10 suction excavators.

As at July 2009 in England the North West Gas Alliance has 3 German-made suction excavators.

Specific jobs

Suction excavator jobs in Italy described in RSP Gmbh's publicity include:

- In the old center of Venice:
  - Cleaning deep silt (accumulated over nearly 40 years) out of the Rio Terà San Polo, which was formerly a narrow open canal, but is now a roofed sewer under a busy street. The excavator sucked through a long hose. Access damage to its roof and the street above was limited to four manhole-sized holes, which afterwards were fitted with manhole covers for future access. This avoided a long smelly traffic-obstruction-causing manual job.
  - Cleaning 1.6 meters deep silt out of the Rio Terà San Leonardo (a roofed sewer, 230 m long, 6 to 13 m wide): similarly.
- The south loggia of the Palazzo della Ragione in Padua: Sucking out a big accumulation of rubble and dust and bird droppings. The space is roofed by medieval vaulting through which only one small access hole was allowed. A 150-meter-long suction hose was used. (In the accompanying photographs the rubble seems to be largely plaster removed from the walls.)
- In Siena: removing about 150 cu.m. of rubble left by building restoration works, which had been dumped in old tunnels cut in tuff.

Vacuum excavation

Vacuum excavation is excavating by high-powered vacuum suction machines. This process significantly reduces the risk of loss of property and injury to workers associated with contacting or cutting underground utilities, as often happens if backhoe, auger, hand digging, or other mechanical methods are used.

Portable vacuum excavation equipment such as suction excavators can quickly dig small deep precisely-controlled holes to uncover buried utilities. Soft excavation technology can dig around buried pipe or cable without the risk of damage inherent with backhoes, excavators, or other mechanical tools.

Typically, vacuum excavation loosens the soil with a blunt-nosed high pressure air lance or water source and immediately vacuums away loosened material. Air and water, when used appropriately, are far less likely than sharp-edged tools to damage underground structures.

Depending on the machine used and soil conditions, a 12-inch-square 5-foot-deep pothole can be completed in 20 minutes or less. Most models are capable of digging deeper, but utility potholes seldom need to be more than six feet deep.

Vacuum excavation is best used in conjunction with conventional underground (one-call) locating services. Because of a preponderance of overlapping buried utility lines, locating devices often incompletely identify all the buried utilities on a site or cannot completely or accurately mark a site.

According to New Mexico One Call 811: *Aligning Change, Locating with Potholing*, "One-call paint marks and flags are the first step in making the process of locating underground utilities safer, the use of vacuum excavation technology adds an additional margin of safety."

Potholing (which here means exposing buried utilities and seeing them to find where and how deep they are) using vacuum, has made it safer to locate underground utilities.

When conventional locating is unworkable due to high densities of buried utilities, potholing can also be used to verify the route of each buried line within the excavation zone. In some cases, the contractor may choose to perform the entire excavation using vacuum methods.

"As vacuum excavation technology and techniques for locating underground utilities has become both readily available and affordable, it's already considered by many municipalities as a Best Practice." Many governmental entities and municipalities no longer allow the use of backhoes for the physical locating of underground utilities, citing the risk of damaging the utility or utilities. Many have implemented policies mandating the use of vacuum excavation.

When conventional locating is unworkable due to high densities of buried utilities, potholing can be used to verify the route of each buried line within the excavation zone. In some cases, the contractor may elect to perform the entire excavation using vacuum methods.

To prevent utility strikes, the use of underground locating services has become the norm, and in most places, is required by law. However, the practice of underground location, while very useful, has its limitations. Locators have been known to incompletely identify all buried utilities or be unable to completely or accurately mark a site because of a preponderance of overlapping buried utility lines.

For these reasons, vacuum excavation techniques can be an effective way to locate, with virtually 100% accuracy, all underground structures in an excavation zone. Vacuum excavation is also typically more cost effective than hand digging.

Through aggressive educational efforts about the safety of vacuum excavation, vacuum excavation is now being mandated in many states and municipalities, and efforts are underway to achieve universal acceptance of vacuum excavation as the preferred technology.

Chapter 10

Well Logging

Well logging, also known as **borehole logging** is the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (*geological* logs) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Well logging is done during all phases of a well's development; drilling, completing, producing and abandoning. Mostly in the oil and gas, groundwater, minerals, geothermal, and for environmental and geotechnical studies.

Electric or geophysical well logs

The oil and gas industry records rock and fluid properties to find hydrocarbon zones in the geological formations intersected by a borehole. The logging procedure consists of lowering a 'logging tool' on the end of a wireline into an oil well (or hole) to measure the rock and fluid properties of the formation. An interpretation of these measurements is then made to locate and quantify potential depth zones containing oil and gas (hydrocarbons). Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, nuclear magnetic resonance, and other properties of the rocks and their contained fluids. Logging is usually performed as the logging tools are pulled out of the hole. This data is recorded either at surface (real-time mode), or downhole (memory mode)to electronic data format and then either a printed record or electronic presentation called a "well log" provided to the client. Well logging is performed at various intervals during the drilling of the well and when the total depth is drilled, which could range in depths from 150 m to 10668 m (500 ft to 35,000 ft) or more.

Electric line is the common term for the armored, insulated cable used to conduct current to downhole tools used for well logging. Electric line can be subdivided into open hole operations and cased hole operations. Other conveyance methods for logging are logging while drilling (LWD), tractor, coiled tubing (real-time and memory), drill pipe conveyed, and slickline (memory, and with new development, some slickline telemetry capability).

Open hole operations, or reservoir evaluation, involves the deployment of tools into a freshly drilled well. As the toolstring traverses the wellbore, the individual tools gather information about the surrounding formations. A typical open hole log will have information about the density, porosity, permeability, lithology, presence of hydrocarbons, and oil and water saturation.

Cased hole operations, or production optimization, focuses of the optimization of the completed oil well through mechanical services and logging technologies. At this point in the well's life, the well is encased in steel pipe, cemented into the well bore and may or may not be producing. A typical cased hole log may show cement quality, production information, formation data. Mechanical services uses jet perforating guns, setting tools, and dump bailors to optimize the flow of hydrocarbons.

Wireline tool types

Typically the wireline tools are cylindrical in shape, usually from 1.5 to 5 inches in diameter. "Open hole" tool combinations can extend to over 100 feet long; "cased hole" tool combinations are often limited in length by the height restrictions imposed by constraints of "lubricator" pipe section required to contain the well pressure while deploying cased hole tools. There are many types of logging tools, ranging from common measurements (pressure and temperature) to advanced rock properties and fracture analysis, fluid properties in the wellbore, or formation properties extending several meters into the rock formation.

1. With sensors without excitation

There are units to measure spontaneous potential (SP), which is a voltage difference between a surface electrode and another electrode located in the downhole instrument, other instruments that measure the natural radiation from natural isotopes of potassium, thorium, etc., to measure pressure and temperature, etc.

2. With sources of excitation and sensors

There are sensor systems consistent with a source of excitation and a sensor. In this type we find acoustic (also called sonic), electric, inductive, magnetic resonance, sensing systems, just to name a few.

3. Instruments that produce some mechanical work, or retrieve a sample of fluid or rock to the surface.

Devices to collect samples of rock, samples of fluid extracted from the rock, and some other mechanical devices.

Types of electric/electronic logs

There are many types of electric/electronic logs and they can be categorized either by their function or by the technology that they use. "Open hole logs" are run before the oil or gas well is lined with pipe or cased. "Cased hole logs" are run after the well is lined with casing or production pipe.

Electric/electronic logs can also be divided into two general types based on what physical properties they measure. Resistivity logs measure some aspect of the specific resistance of the geologic formation. There are about 17 types of resistivity logs.

Porosity logs measure the fraction or percentage of pore volume in a volume of rock. Most porosity logs use either acoustic or nuclear technology. Acoustic logs measure characteristics of sound waves propagated through the well-bore environment. Nuclear logs utilize nuclear reactions that take place in the downhole logging instrument or in the formation. Nuclear logs include density logs and neutron logs, as well as gamma ray logs which are used for correlation. The basic principle behind the use of nuclear technology is that a neutron source placed near the formation of which the porosity is required to be measured will result in neutrons being scattered by the hydrogen atoms, largely those present in the formation fluid. Since there is little difference in the neutrons scattered by hydrocarbons or water, the porosity measured gives a figure close to the true physical porosity whereas the figure obtained from electrical resistivity measurements is that due to the conductive formation fluid. The difference between neutron porosity and electrical porosity measurements therefore indicates the presence of hydrocarbons in the formation fluid.

History

Conrad and Marcel Schlumberger, who founded Schlumberger Limited in 1926, are considered the inventors of electric well logging. Conrad developed the Schlumberger array, which was a technique for prospecting for metal ore deposits, and the brothers adopted that surface technique to subsurface applications. On September 5, 1927, a crew working for Schlumberger lowered an electric sonde or tool down a well in Pechelbronn, Alsace, France creating the first well log. In modern terms, the first log was a resistivity log that could be described as 3.5-meter upside-down lateral log.

In 1931, Henri George Doll and G. Dechatre, working for Schlumberger, discovered that the galvanometer wiggled even when no current was being passed through the logging cables down in the well. This led to the discovery of the spontaneous potential (SP) which was as important as the ability to measure resistivity. The SP effect was produced naturally by the borehole mud at the boundaries of permeable beds. By simultaneously recording SP and resistivity, loggers could distinguish between permeable oil-bearing beds and impermeable nonproducing beds.

In 1940, Schlumberger invented the spontaneous potential dipmeter; this instrument allowed the calculation of the dip and direction of the dip of a layer. The basic dipmeter was later enhanced by the resistivity dipmeter (1947) and the continuous resistivity dipmeter (1952).

Oil-based mud (OBM) was first used in Rangely Field, Colorado in 1948. Normal electric logs require a conductive or water-based mud, but OBMs are nonconductive. The solution to this problem was the induction log, developed in the late 1940s.

The introduction of the transistor and integrated circuits in the 1960s made electric logs vastly more reliable. Computerization allowed much faster log processing, and dramatically expanded log data-gathering capacity. The 1970s brought more logs and computers. These included combo type logs where resistivity logs and porosity logs were recorded in one pass in the borehole.

The two types of porosity logs (acoustic logs and nuclear logs) date originally from the 1940s. Sonic logs grew out of technology developed during World War II. Nuclear logging has supplemented acoustic logging, but acoustic or sonic logs are still run on some combination logging tools.

Nuclear logging was initially developed to measure the natural gamma radiation emitted by underground formations. However, the industry quickly moved to logs that actively bombard rocks with nuclear particles. The gamma ray log, measuring the natural radioactivity, was introduced by Well Surveys Inc. in 1939, and the WSI neutron log came in 1941. The gamma ray log is particularly useful as shale beds which often provide a relatively low permeability cap over hydrocarbon reservoirs usually display a higher level of gamma radiation. These logs were important because they can be used in cased wells (wells with production casing). WSI quickly became part of Lane-Wells. During World War II, the US Government gave a near wartime monopoly on open-hole logging to Schlumberger, and a monopoly on cased-hole logging to Lane-Wells. Nuclear logs continued to evolve after the war.

The nuclear magnetic resonance log was developed in 1958 by Borg Warner. Initially the NMR log was a scientific success but an engineering failure. However, the development of a continuous NMR logging tool by Numar (now a subsidiary of Halliburton) is a promising new technology.

Many modern oil and gas wells are drilled directionally. At first, loggers had to run their tools somehow attached to the drill pipe if the well was not vertical. Modern techniques now permit continuous information at the surface. This is known as logging while drilling (LWD) or measurement-while-drilling (MWD). MWD logs use mud pulse technology to transmit data from the tools on the bottom of the drillstring to the processors at the surface.

Logging while drilling

In the 1980s, a new technique, logging while drilling (LWD), was introduced which provided similar information about the well. Instead of sensors being lowered into the well at the end of wireline cable, the sensors are integrated into the drill string and the measurements are made while the well is being drilled. While wireline well logging occurs after the drill string is removed from the well, LWD measures geological parameters while the well is being drilled. However, because there are no wires to the surface, data are recorded downhole and retrieved when the drill string is removed from the hole. A small subset of the measured data can also be transmitted to the surface in real time via pressure pulses in the well's mud fluid column. This mud telemetry method provides a bandwidth of much less than 100 bits per second, although, as drilling through rock is a fairly slow process, data compression techniques mean that this is an ample bandwidth for real-time delivery of information.

Logging measurement types

Logging measurements are quite sophisticated. The prime target is the measurement of various geophysical properties of the subsurface rock formations. Of particular interest are porosity, permeability, and fluid content. Porosity is the proportion of fluid-filled space found within the rock. It is this space that contains the oil and gas. Permeability is the ability of fluids to flow through the rock. The higher the porosity, the higher the possible oil and gas content of a rock reservoir. The higher the permeability, the easier for the oil and gas to flow toward the wellbore. Logging tools provide measurements that allow for the mathematical interpretation of these quantities.

Beyond just the porosity and permeability, various logging measurements allow the interpretation of what kinds of fluids are in the pores—oil, gas, brine. In addition, the logging measurements are used to determine mechanical properties of the formations. These mechanical properties determine what kind of enhanced recovery methods may be used (tertiary recovery) and what damage to the formation (such as erosion) is to be expected during oil and gas production.

The types of instruments used in well logging are quite broad. The first logging measurements consisted of basic electrical resistivity logs and spontaneous potential (SP) logs, introduced by the Schlumberger brothers in the 1920s. Tools later became available to estimate porosity via sonic velocity and nuclear measurements. Tools are now more specialized and better able to resolve fine details in the formation. Radiofrequency transmission and coupling techniques are used to determine electrical conductivity of fluid (brine is more conductive than oil or gas). Sonic transmission characteristics (pressure waves) determine mechanical integrity. Nuclear magnetic resonance (NMR) can determine the properties of the hydrogen atoms in the pores (surface tension, etc.). Nuclear scattering (radiation scattering), spectrometry and absorption measurements can determine density and elemental analysis or composition. High resolution electrical or acoustical imaging logs are used to visualize the formation, compute formation dip, and analyze thinly-bedded and fractured reservoirs.

In addition to sensor-based measurements above, robotic equipment can sample formation fluids which may then be brought to the surface for laboratory examination. Also, controlled flow measurements can be used to determine in situ viscosity, water and gas cut (percentage), and other fluid and production parameters.

Geological logs

Geological logs use data collected at the surface, rather than by downhole instruments. The geological logs include *drilling time logs*, *core logs*, *sample logs*, and *mud logs*. Mud logs have become the oil industry standard.

Drilling time logs record the time required to drill a given thickness of rock formation. A change in the drilling rate or penetration rate usually means a change in the type of rock penetrated by the bit. The drilling time is expressed as minutes per foot, while the rate of penetration is usually expressed as feet per hour. Therefore, drilling time is the inverse of penetration rate.

Sample logs are made by examining cuttings, which are bits of rock circulated to the surface by the drilling mud in rotary drilling. The cuttings have traveled up the wellbore suspended in the drilling fluid or mud which was pumped into the wellbore via the drill string/pipe and they return to the surface via the annulus, then to the shale shakers via the flow line. Cuttings are then separated from the drilling fluid as they move across the shale shakers and are sampled at regular depth intervals. These rock samples are analyzed and described by the wellsite geologist or mudlogger.

Mud logs are prepared by a mud logging company contracted by the operating company. One parameter a typical mud log displays is the formation gas (gas units or ppm). "The gas recorder usually is scaled in terms of arbitrary gas units, which are defined differently by the various gas-detector manufactures. In practice, significance is placed only on relative changes in the gas concentrations detected." The current industry standard mud log normally includes real-time drilling parameters such as rate of penetration (ROP), lithology, gas hydrocarbons, flow line temperature (temperature of the drilling fluid) and chlorides but may also include mud weight, estimated pore pressure and corrected d-exponent (corrected drilling exponent) for a pressure pack log. Other information that is normally notated on a mud log include lithology descriptions, directional data (deviation surveys), weight on bit, rotary speed, pump pressure, pump rate, viscosity, drill bit info, casing shoe depths, formation tops, mud pump info, to name just a few.

Wireline log

A continuous measurement of formation properties w ith electrically powered instruments to infer properties and make decisions about drilling and production operations. The record of the measurements, typically a long strip of paper, is also called a log. Measurements include electrical properties (resistivity at various frequencies), sonic properties, active and passive nuclear measurements, dimensional measurements of the wellbore, formation fluid sampling, formation pressure measurement, wireline-conveyed sidewall coring tools, and others. In wireline measurements, the logging tool (or probe) is lowered into the open wellbore on a multiple conductor, contra-helically armored wireline. Once lowered to the bottom of the interval of interest, the measurements are taken on the way out of the wellbore. This is done in an attempt to maintain tension on the cable (which stretches) as constant as possible for depth correlation purposes. (The exception to this practice is in certain hostile environments in which the tool electronics might not survive the temperatures on bottom for the amount of time it takes to lower the tool and then record measurements while pulling the tool up the hole. In this case, "down log" measurements might actually be conducted on the way into the well, and repeated on the way out if possible.) Most wireline measurements are recorded continuously even though the probe is moving. Certain fluid sampling and pressure-measuring tools require that the probe be stopped, increasing the chance that the probe or the cable might become stuck. LWD tools take measurements in much the same way as wireline-logging tools, except that the measurements are taken by a self-contained tool near the bottom of the bottomhole assembly and are recorded downward (as the well is deepened) rather than upward from the bottom of the hole (as wireline logs are recorded).

Memory log

This method of data acquisition involves recording the sensor data into a down hole memory, rather than transmitting "Real Time" to surface. There are some advantages and disadvantages to this memory option.

- The tools can be conveyed into wells where the trajectory is deviated or extended beyond the reach of conventional Electric Wireline cables. This can involve a combination of weight to strength ratio of the electric cable over this extended reach. In such cases the memory tools can be conveyed on Pipe or Coil Tubing.
- The type of sensors are limited in comparison to those used on Electric Line, and tend to be focussed on the cased hole,production stage of the well. Although there are now developed some memory "Open Hole" compact formation evaluation tool combinations. These tools can be deployed and carried downhole concealed internally in drill pipe to protect them from damage while running in the hole, and then "Pumped" out the end at depth to initate logging. Other basic open hole formation evaluation memory tools are available for use in "Commodity" markets on slickline to reduce costs and operating time.
- In cased hole operation there is normally a "Slick Line" intervention unit. This uses a solid mechanical wire (.82 - .125 inches in OD), to manipulate or otherwise carry out operations in the well bore completion system. Memory operations are often carried out on this Slickline conveyance in preference to mobilizing a full service Electric Wireline unit.
- Since the results are not known until returned to surface, any realtime well dynamic changes cannot be monitored real time. This limits the ability to modify or change the well down hole production conditions accuratly during the memory logging by changing the surface production rates. Something that is often done in Eletric Line operations.
- Failure during recording is not known until the memory tools are retrieved. This loss of data can be a major issue on large offshore (expensive) locations. On land locations (e.g. South Texas, US) where there is what is called a "Commodity" Oil service sector, where logging often is without the rig infrastructure. this is less problematic, and logs are often run again without issue.

Information use

In the oil industry, the well and mud logs are usually transferred in 'real time' to the operating company, which uses these logs to make operational decisions about the well, to correlate formation depths with surrounding wells, and to make interpretations about the quantity and quality of hydrocarbons present. Specialists involved in well log interpretation are called log analysts.

Well logging images

Wireline attached to top of Christmas Tree

Oil Well Top of Wireline

Wireline Truck with drum (inside)

Wax being removed off a wireline wax knife

BO shifting tool

Chapter 11

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

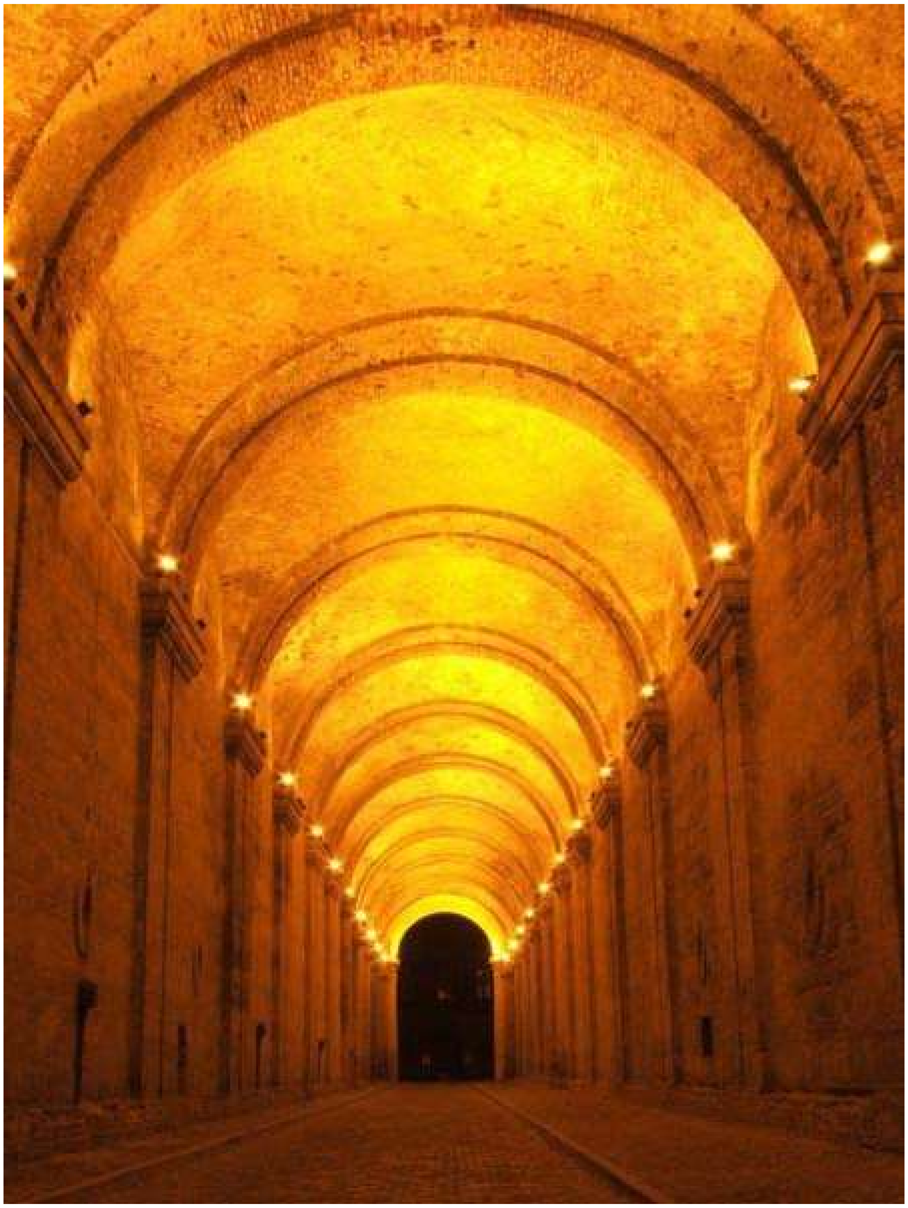
Double-deck tunnel

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

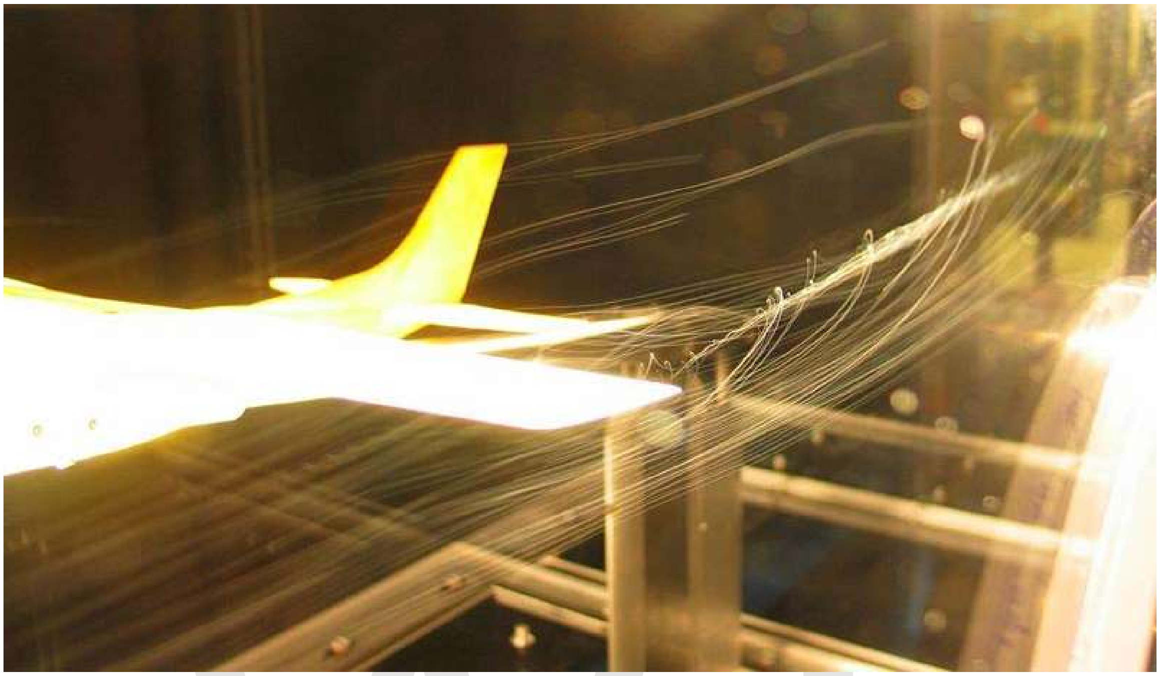
The vehicles using a tunnel can outgrow it, requiring replacement or enlargement. The original single line Gib Tunnel near Mittagong was replaced with a double line tunnel, with the original tunnel used for growing mushrooms. The Rhyndaston Tunnel was enlarged using a borrowed Tunnel Boring Machine so 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 12

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

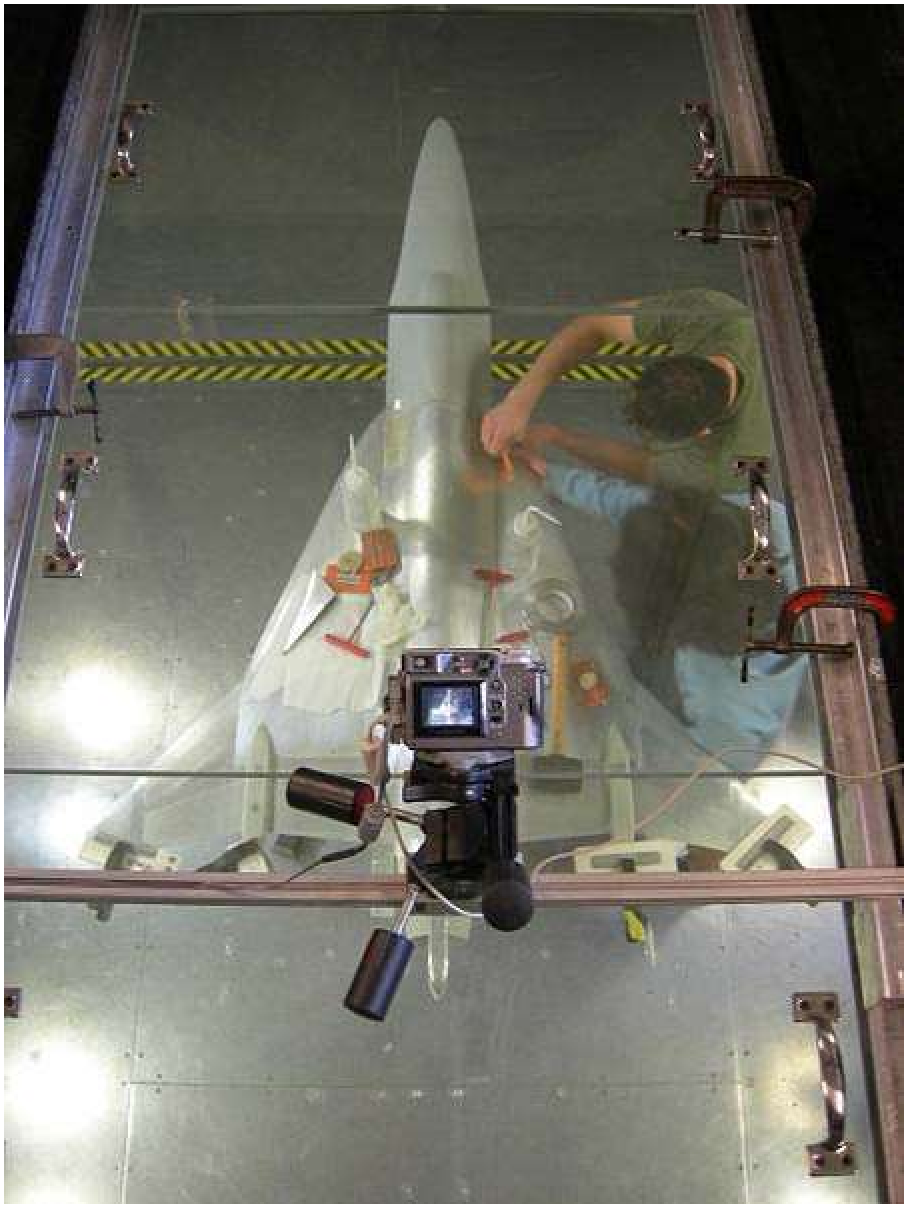
In 1941 the US constructed one of the largest wind tunnels at that time at Wright Field in Dayton, Ohio. This wind tunnel starts at 45 feet and narrows to 20 feet in diameter. Two 40 foot fans were driven by a 40,000hp electric motor. Large scale aircraft models could be tested at air speeds of 400mph.

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 jet-powered, 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.

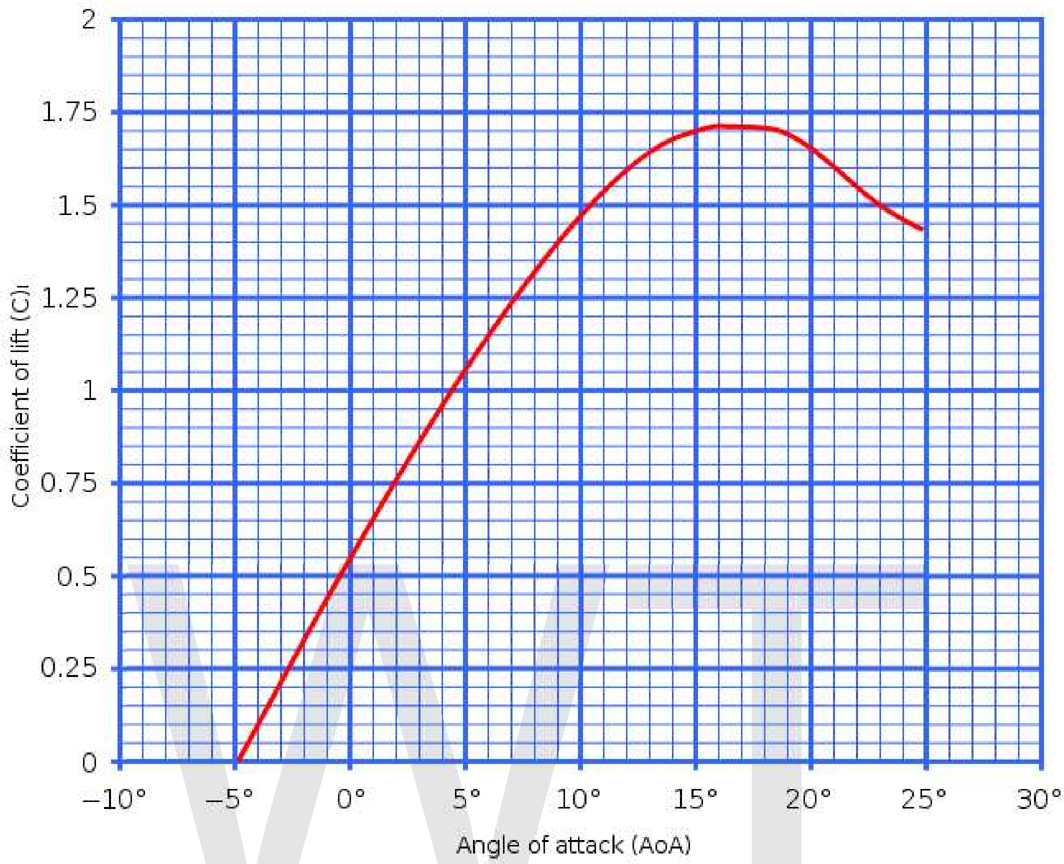
Lighting is usually recessed into the circular walls of the tunnel and shines in through windows. If the light were mounted on the inside surface of the tunnel in a conventional manner, the light bulb would generate turbulence as the air blows around it. Similarly, observation is usually done through 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

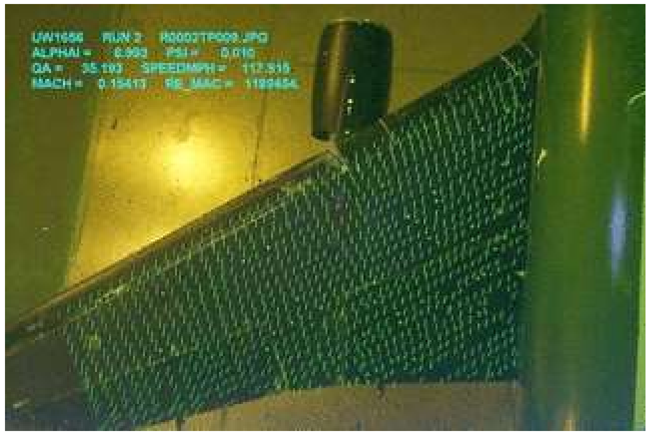
Because air is transparent it is difficult to directly observe the air movement itself. Instead, multiple methods of both quantitative and qualitative flow visualization methods have been developed for testing in a wind tunnel.

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.

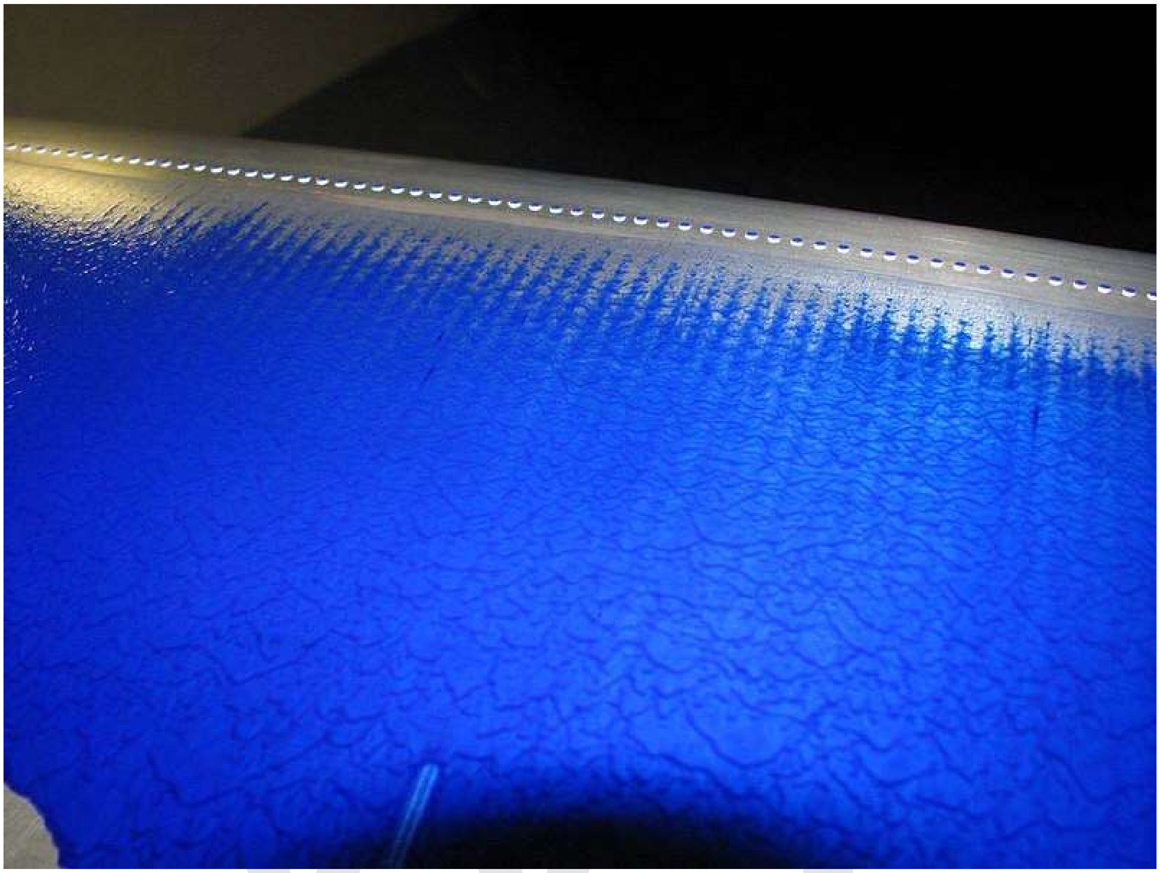
- Evaporating suspensions

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

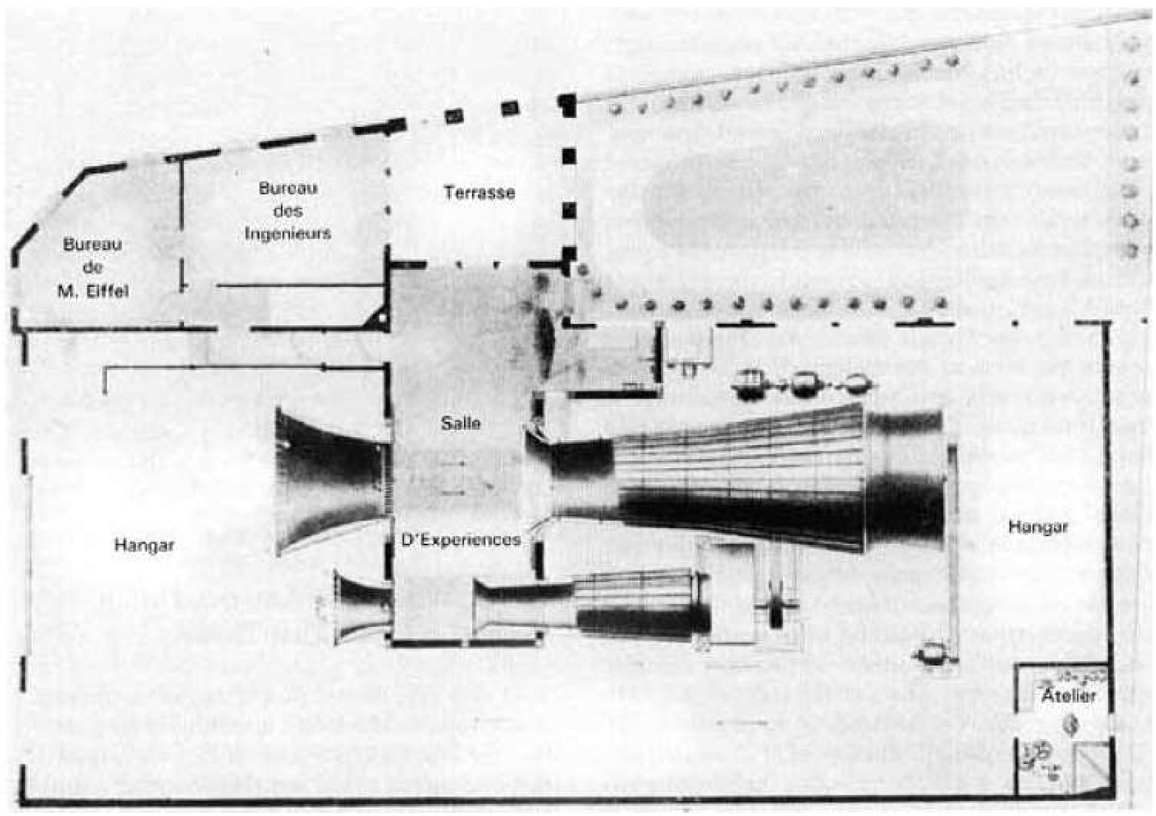
Air is not always the best test medium to study small-scale aerodynamic principles, due to the speed of the air flow and airfoil movement. A study of fruit fly wings designed to understand how the wings produce lift was performed using a large tank of mineral oil and wings 100 times larger than actual 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 13

Subsonic and Transonic Wind Tunnel

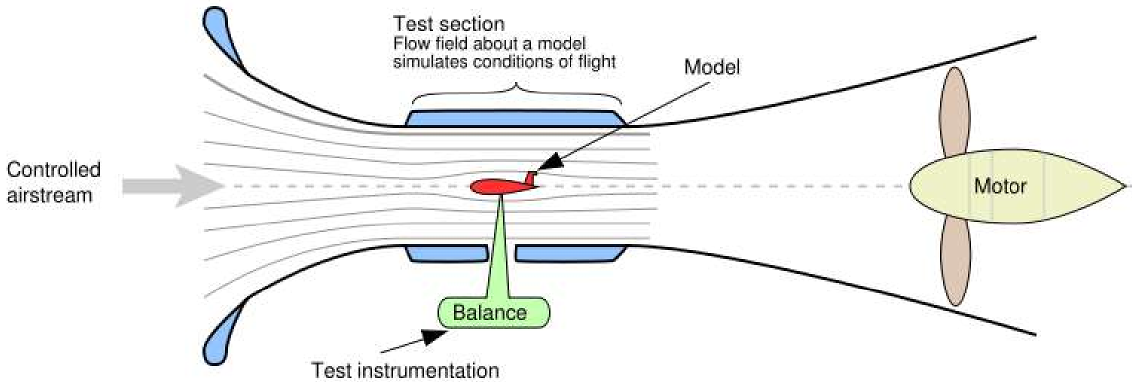


Eiffel wind tunnel

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:

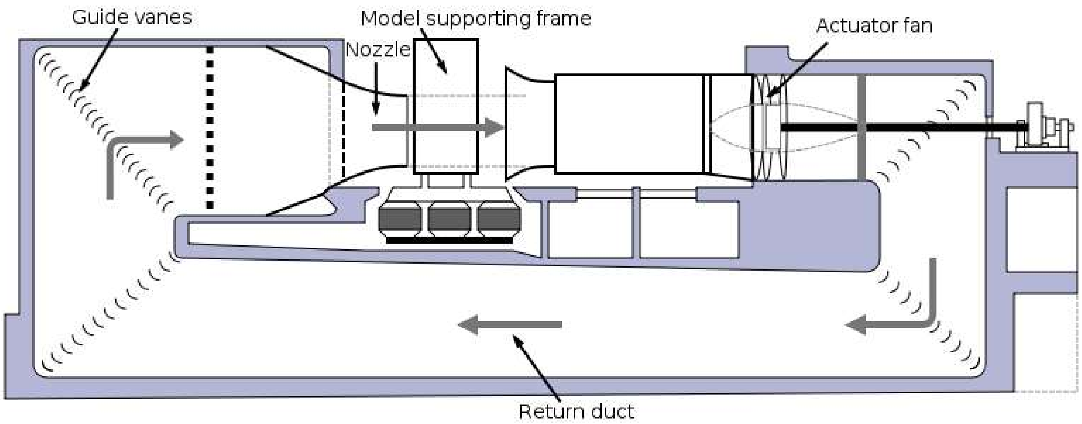
$$P_{total} = P_{static} + P_{dynamic} = P_s + \frac{1}{2}\rho V^2$$

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:

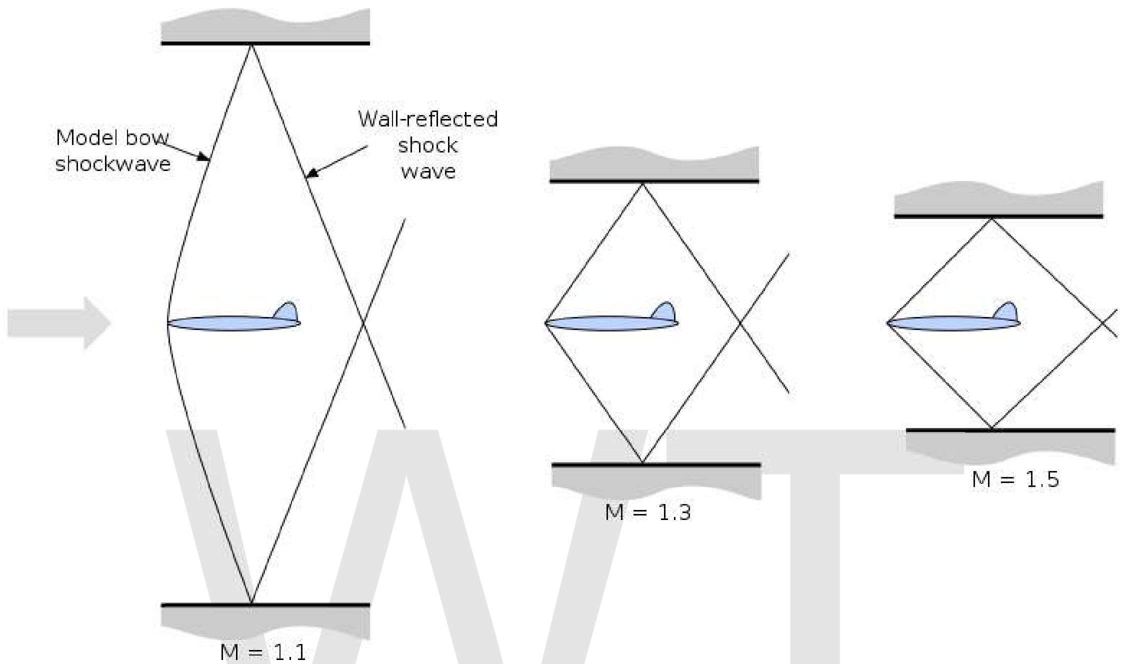
$$\frac{dA}{A} = (M^2 - 1)\frac{dV}{V}$$

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 14

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

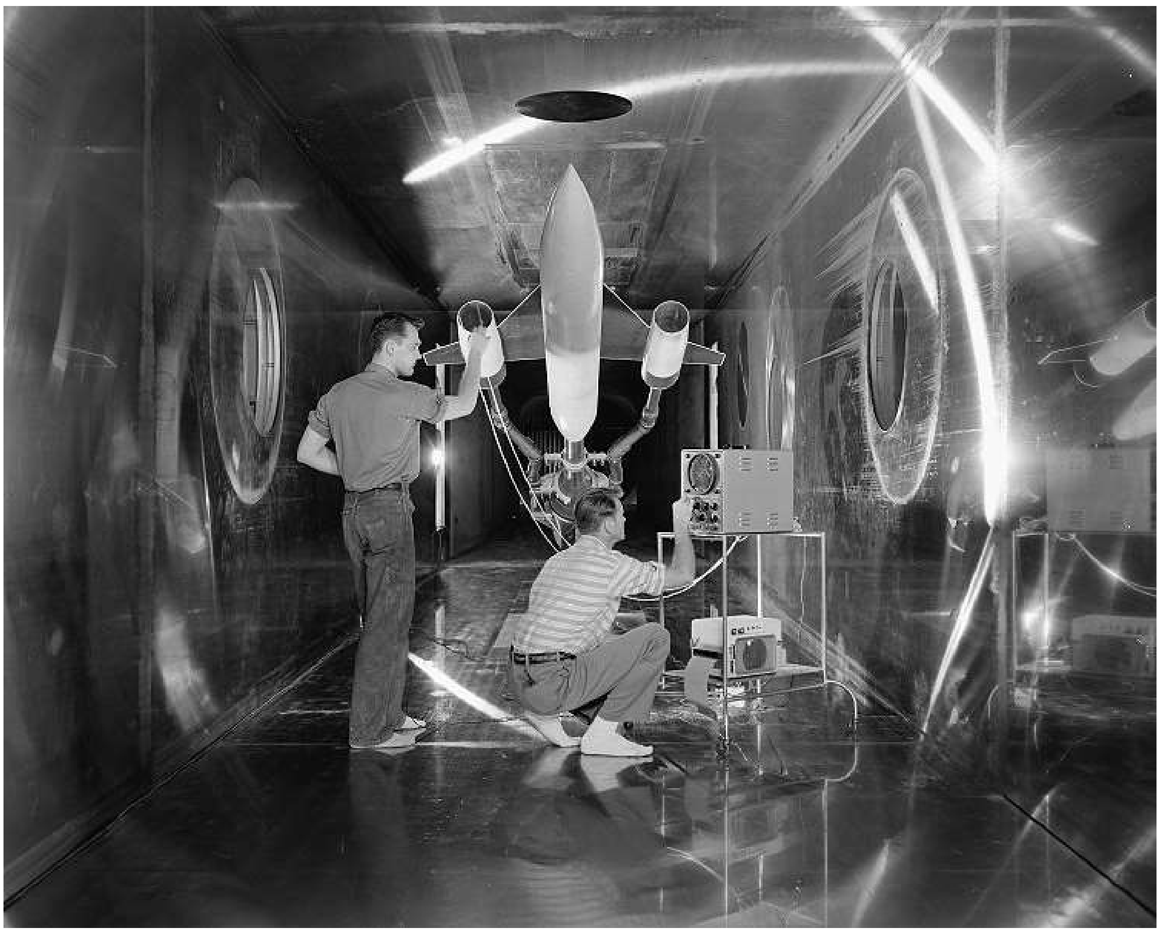
The first human to fly in a vertical wind tunnel was Jack Tiffany in 1964 at Wright Patterson Air Force Base located in Greene and Montgomery County, Ohio.

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:

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

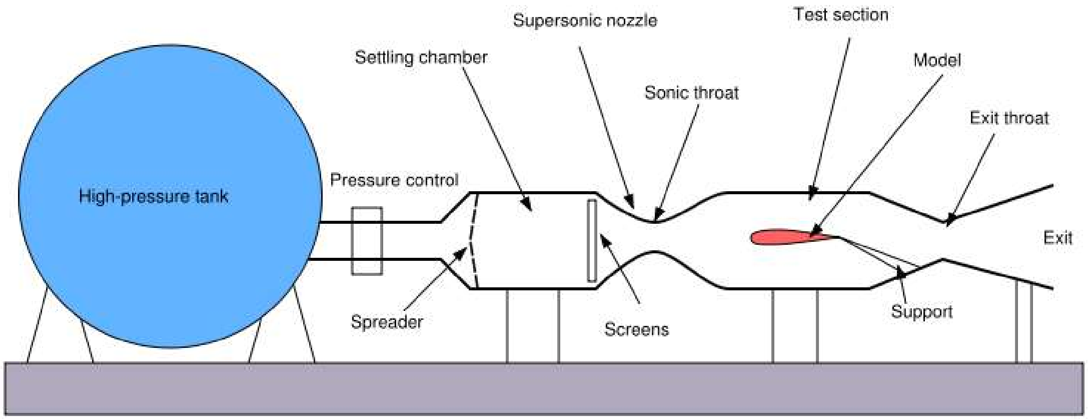
with T_t = 330K: T_m = 70K at M_m = 4

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 15

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.

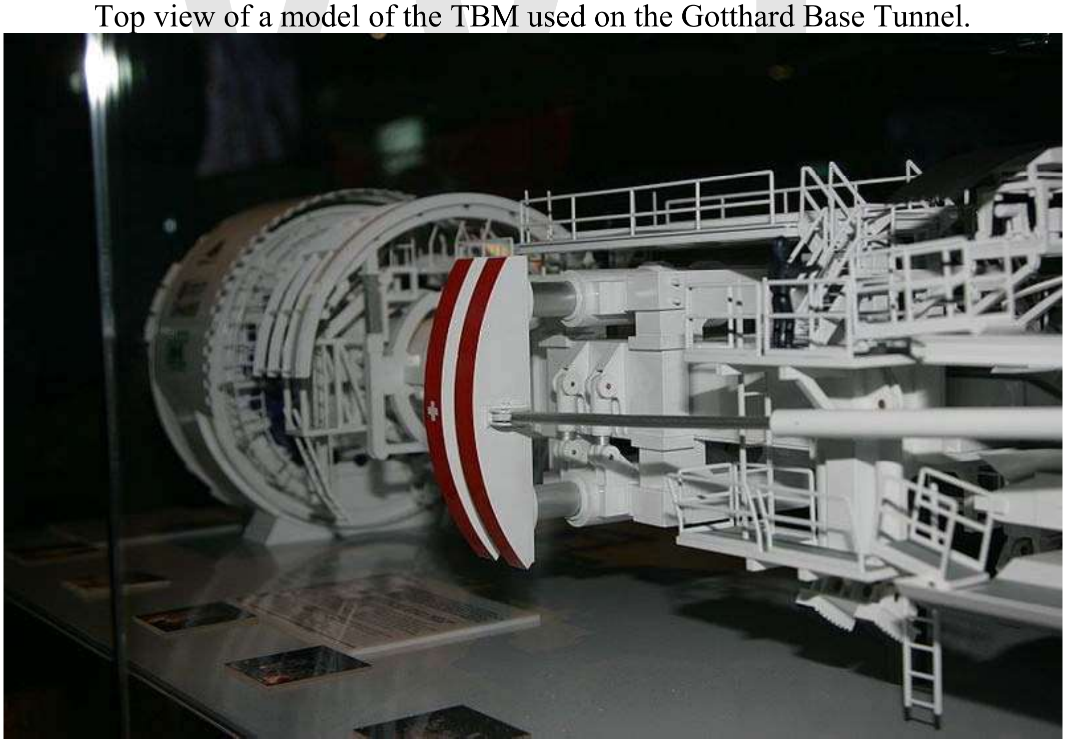
Tunnel boring machines are used as an alternative to drilling and blasting (D&B) methods in rock and conventional 'hand mining' in soil. TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the 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 16

Submerged Floating Tunnel

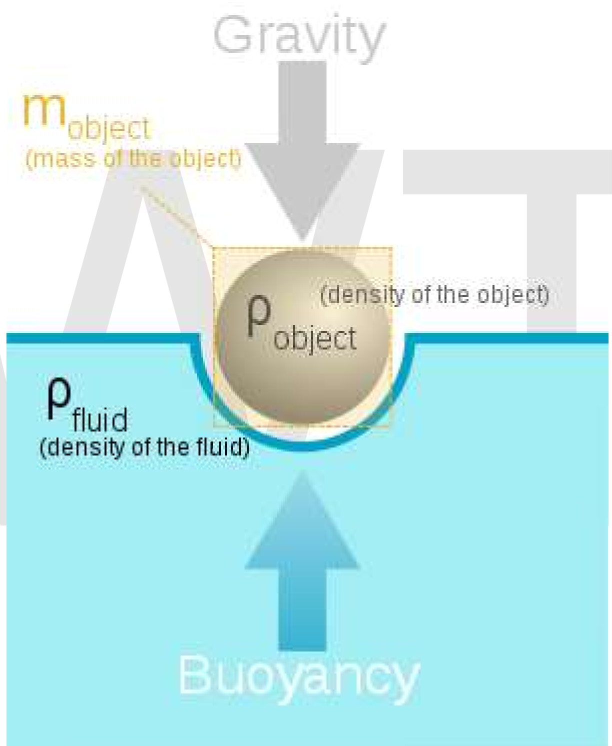
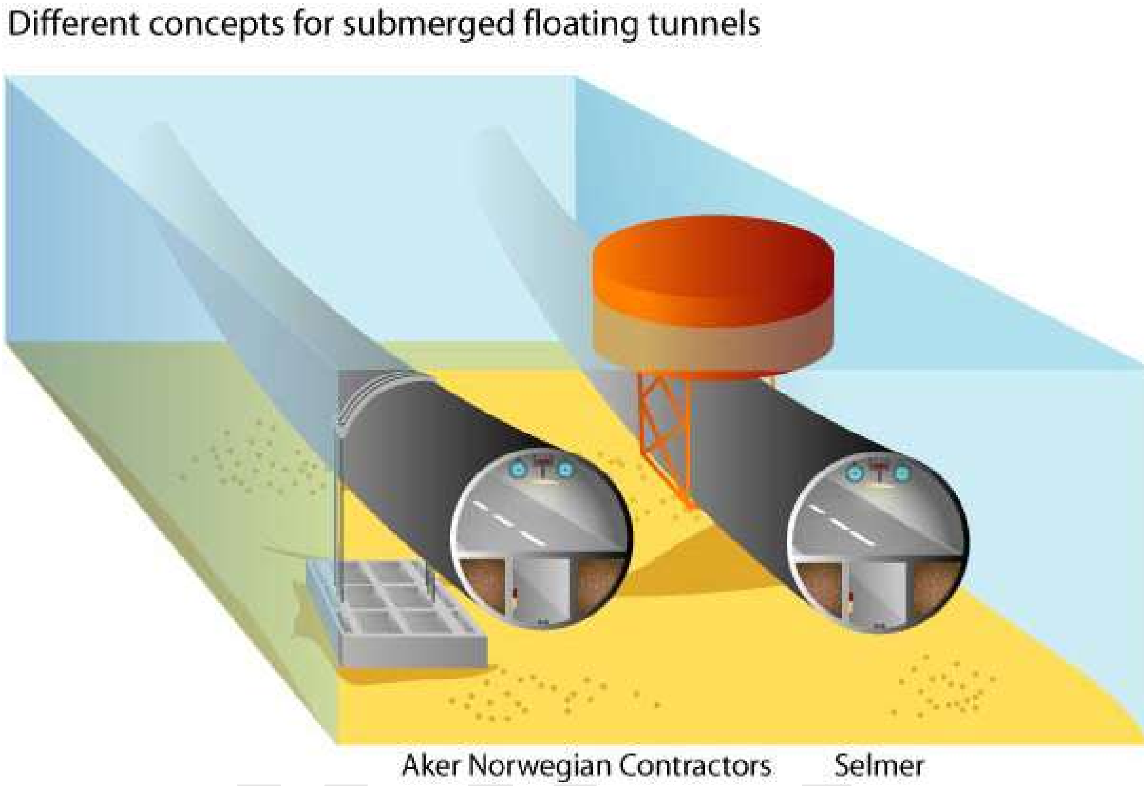


Diagram of the buoyancy effect

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

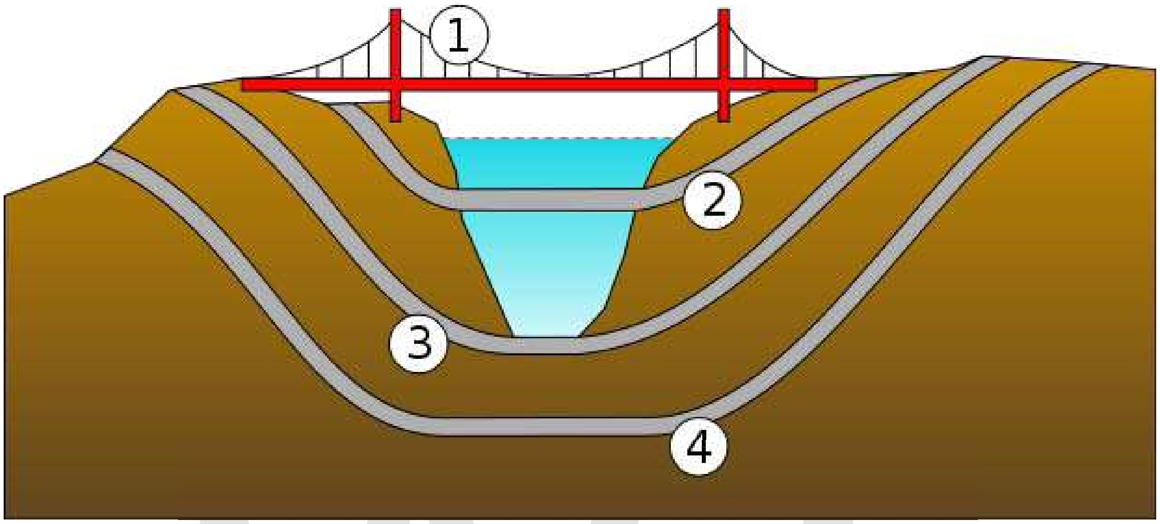


Two types of Submerged Floating tunnels

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 17

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.

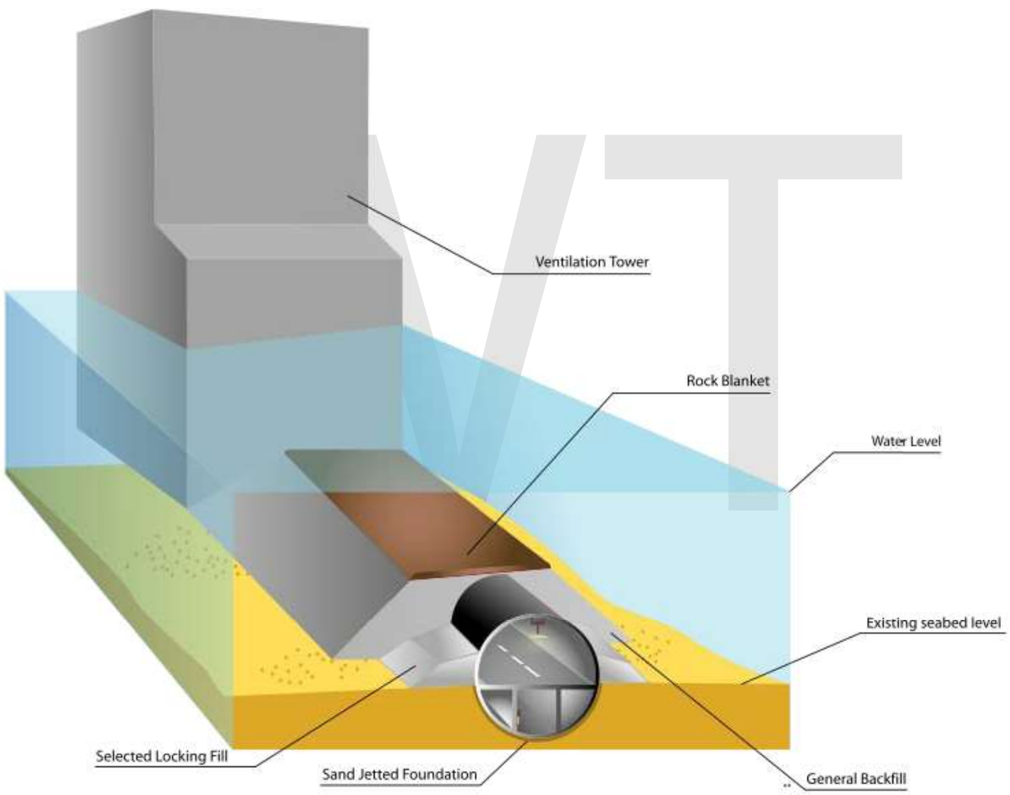
Accidents

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.

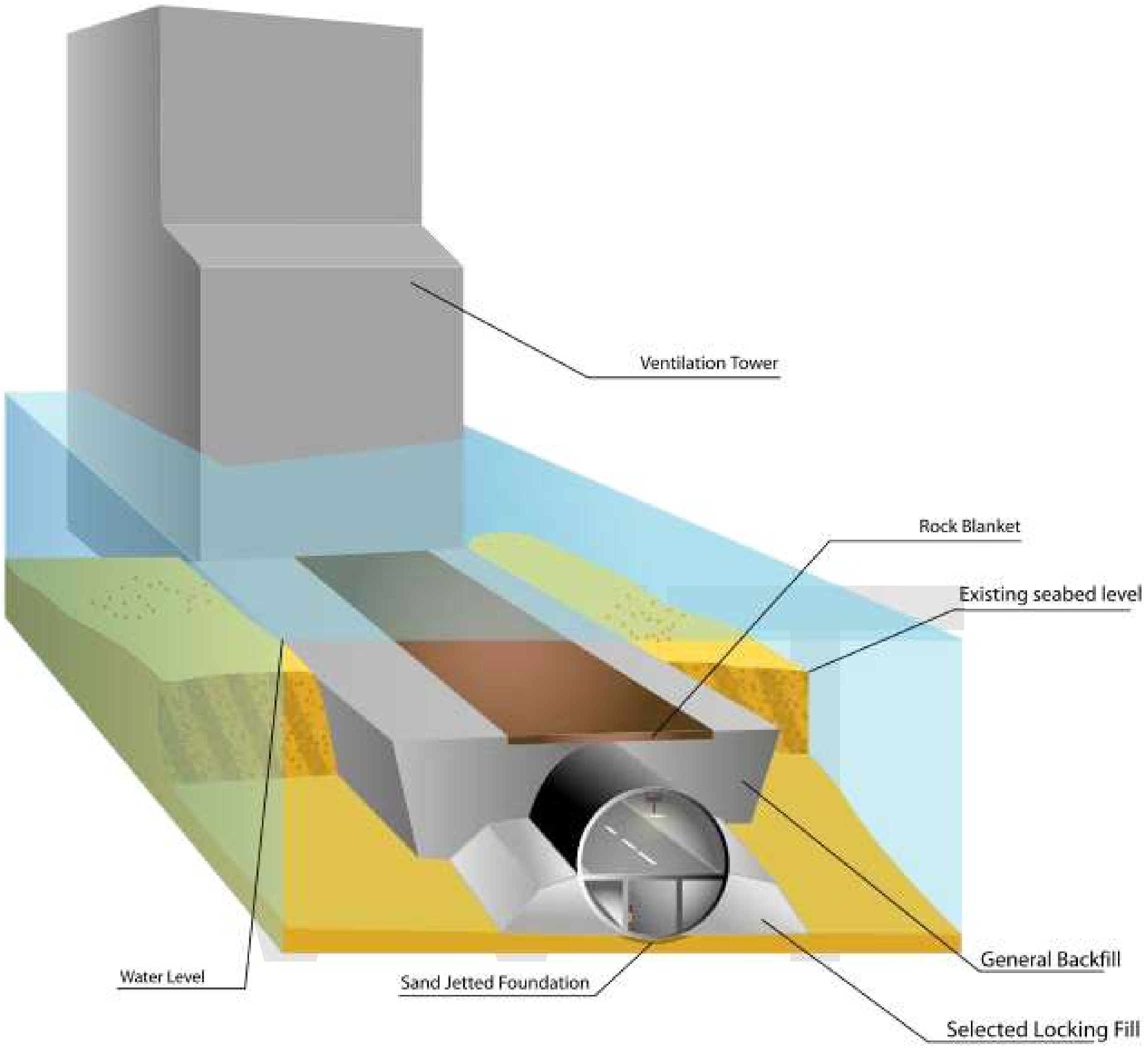
If a culvert made of steel is not properly galvanized, the culvert can eventually collapse, again disrupting the road or railway above it. This happened at a culvert near Gosford, New South Wales in 2007, killing five.

Chapter 18

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