3 Tunnelling

1. Introduction

Tunnels can be defined as underground passages constructed for the purpose of transportation connection between two points.

2. Type of Tunnels

There are many types of tunnels and can be classified in many ways:

<table>
<thead>
<tr>
<th>Classified by</th>
<th>Example of tunnels</th>
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<tbody>
<tr>
<td>Purpose</td>
<td>Railway tunnels, metro system, highway tunnels, pedestrian tunnels, water tunnels, sewage tunnels, services tunnels, storage tunnels.</td>
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<tr>
<td>Geological location / condition</td>
<td>Rock tunnels, earth tunnels, and submerged tunnels.</td>
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<tr>
<td>Cross-sectional shapes</td>
<td>Rectangular shape, circular shape, elliptical shape, egg shape, horse shoe shape, and segmental shape.</td>
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3. Shapes of Tunnel Lining

The shapes of tunnel linings are usually determined by their purpose, ground conditions, construction method and/or lining materials.
3.1 Rectangular shape
Rectangular shaped tunnels are usually adopted by the cut and cover method. It is particularly suitable for pedestrian and highway tunnels. On the other hand, multi-lane submerged highway tunnels are often in rectangular shape.

3.2 Elliptical shape / Egg shape
Elliptical shape tunnels have the advantages for the transportation of sewer. The smaller cross section at the bottom maintains the flow at the required self-cleaning velocity. However, due to the difficulty in construction, circular shape ones are more common.

3.3 Circular shape
A circular shape tunnel has the greatest cross-sectional area to perimeter ratio. They are often associated with TBM or the shield tunnelling methods.

3.4 Horseshoe / segmental shape
They are commonly used for rock tunnelling. It has the advantages of utilising the compressive strength of concrete in resisting the loading by means of arch action and the base is wide enough for traffic.

Different Shapes of Tunnels
4. **Tunnel lining materials**

Permanent linings are required in most tunnels, always in soft ground and frequently in rock. They are required for two purposes: structurally to retain the earth and water pressure, and operationally to provide an internal surface appropriate to the function of the tunnel.

The principal materials for permanent lining of bored tunnels are:

4.1 **Brickwork, blockwork and masonry**

Brickwork, blockwork and masonry had been used for tunnel lining but now they are obsolete.

4.2 **Insitu concrete**

Insitu concrete lining is frequently in rock tunnelling where the roof is able to stay unsupported temporary. Specially designed travelling formwork is used for casting the concrete.

![Travelling Form for Tunnel Lining Construction](image)
4.3 Preformed segments

Preformed segments may be made of cast iron, steel or normal reinforced concrete. This type of lining usually comes with TBM or shield tunnelling methods.

The segments are jointed together by bolting and the joints are sealed with neoprene gasket. Sometimes the joints are also caulked with rubberised bituminous strips. Voids behind the preformed segments are filled by bentonite cement grout.
4.3 Sprayed Concrete

Sprayed concrete linings usually compose of rock bolts, wire mesh, steel ribs and a thin layer or sprayed concrete. This kind of lining is rather flexible than other types of linings. The use of sprayed concrete lining is usually associated with the New Austrian Tunnelling Method (NATM). NATM technology will be discussed later.
5. Tunnelling Methods on Land

5.1 Open Cut

Open cut method often refers to excavation with battered sides such that no lateral support is required. In its simplest form, a trench is excavated, the tunnel structure is built, the trench is backfilled and the surface is restored. Precast tunnel units can also be employed to speed up to construction process.

The major problem of this method is the procession of land so that it is not too suitable in urban areas. Moreover, it is only suitable for shallow tunnels only because with increased depth, direct costs of trench excavation and backfilling increase rapidly.

5.1 Cut and Cover Method

The construction process of cut and cover method is very similar to that of open cut method except that the excavation sides are vertical and temporary supported are provided.

The main problems associated with cut and cover method are the stability of the soft ground, impact on the existing underground services & utilities and traffic disruption in urban areas.
Temporary steel decks may be used to maintain the traffic while the construction works proceeds underneath. This method is also only suitable for high level tunnels.

### 4.2 Pre-Deck Method

Same as the open-cut method, the pre-deck method is suitable for high level tunnels. The tunnel walls are constructed by the diaphragm walling method first and then the upper surface of the ground is removed. The upper deck of the tunnel is cast supported on the diaphragms. It is then backfilled and the road surface is reinstated. Now the tunnel excavation can started from both ends of the tunnel without the fear of collapse and with minimum disturbance to traffic and services.
4.3 Pipe jacking Method

This method can be used for the installation of pipes from 150 mm to 4 m diameter, or box section up to 7 x 4 m, but it is mainly employed on the larger diameter pipes of over 1 m.

This method is very suitable for installing services under roads and railway embankments without creating disturbance to traffic.

The method consists of forming pits at both ends of the proposed tunnel. A thrust wall is constructed to provide jacking reaction and pipe segments are jacked into the soil.

For small diameter pipes, bullet-shaped solid metal heads are fixed to the leading end of the pipe, which is jacked into the ground displacing the earth.

For tunnels of diameter 1 m or above, the leading pipe is fitted with a steel shield to aid the driving process. The shield provides protection under which the

Pipe Jacking

Source: R. Chudley

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For tunnels of diameter 1 m or above, the leading pipe is fitted with a steel shield to aid the driving process. The shield provides protection under which the
workers excavate the tunnel face. New pipe segments are added from the starting pit and jacked forward one by one until the pipe length reaches the opposite pit.

**Micro TBM**

Another modern method of boring the tunnel shaft is by using micro TBM. The excavated spoil is liquefied by mixing with bentonite slurry and removed by pump and pipeline.

For large diameter pipes or for long pipes, the friction will be very great and it creates problems in providing suitable jacking reaction. A method to counteract the friction is the introduction of intermediate jacks. The intermediate jacks are fixed on steel sleeves which are installed at suitable intervals along the pipe length. The line is then jacked forward in a caterpillar fashion. In addition, bentonite slurry can be introduced from the rear of the driving shield as lubricant to reduce the friction.
4.4 Shield Tunnelling Method

The technique of shield tunnelling method is very similar to pipe jacking method, except that prefabricated segments are used for lining and are installed right behind the shield.

Use of Compressed Air in Tunneling

When tunnelling in water bearing ground, ground water infiltration will create problems. The ground water can be excluded by the introduction of compressed air. This method is especially suitable for excluding water from fine silts or soft clays. Compressed air also provides a counterbalancing force against the inward pressure thus reducing risk of collapsing of the tunnel face.

A great deal of air may leak through the tunnel wall and face. To prevent excessive loss of pressure, caulking should be done. One method is to cover the tunnel face with polythene sheeting when the exaction is not carrying out. An alternative method is to spray the tunnel face with bentonite slurry. The method is more convenience and more effective for fine soil.
The appropriate working pressure is about 200 kN/m² (2 bar), but sometimes as high as 3.4 bar is used. When working compressed air environment, air will dissolved into our blood. Air bubble may form and block our blood stream if decompression procedure is not strictly followed before leaving the compressive air environment after work.

4.5 Tunnel Boring Machine (TBM)

To avoid the need of miners working in compressed air and to eliminate the risk of collapse of tunnel face, tunnel boring machines (TBM) are developed for such purpose.

By definition, all machines used for boring tunnels are tunnel boring machines. However, a TBM often refers to a large diameter cylindrical shield, equipped with a rotating cutterhead at the front, a mucking device, and frequently an automatic segment erector.

Some sophisticated Tunnel Boring Machine:

4.5.1 Earth Pressure Balanced Shield

A cutterhead consisted of 3 to 8 radial arms with chisels is fitted in the front of the TBM. A bulkhead is provided behind the cutterhead to form a pressure chamber. Spoil is stored in the chamber is discharged in a controlled rate. The pressure built up in the chamber is utilized to balance the external pressure.
4.5.2 Bentonite Shield

A bentonite shield is equipped with a pressure bulkhead and a chamber. The chamber is filled with bentonite slurry to balance the external pressure. The slurry also liquefies the spoil which can then be transported out by pumping.
4.5.1.3 Rock TBM

In rock TBM, disc cutters are used to cut the rock. The rock failure is actually by shear that occurs due to the penetration of the cutter tip into the face. The cutters are manufactured with hardened tool steel and range in size of typically 300 to 500 mm in diameter. The cutters are mounted on the cutterhead in a pattern and number that will provide coverage over the entire face.

4.6 Advantages of using TBM

1. Fast rate of advance in producing a round, smooth and un-shattered bores.
2. Overbreak is less than 5% which is much less than other methods.
3. Excavation formation is not weakened by the operation hence less ground support is required.
4. Eliminate the need to work compressed air.
5. No risk of collapse of the excavation face.
6. Cost reduction for long tunnels (over 2 km).
4.7 Limitations of using TBM are

1. High initial cost renders it expensive for short tunnels.
2. High cost for wear and tear when driving tunnels in hard rock.
3. It is limited to driving circular tunnels and cannot be used for other cross section.

4.6 Drill and Blast Method for Rock Tunnelling

This method is suitable in medium to strong rock. By jack hammers, blast holes are drilled on the tunnel face. Explosives are loaded in the blast holes and then blasting is taken place.

R.C. tunnel lining can be cast by using travelling formwork, or more often, the tunnel lining is formed by sprayed concrete.

There are various methods of attacking the rock face. The choice depends on the size and shape of tunnel and the available equipment.
4.6.1. Full Face Method

In this method, the whole tunnel face is blasted at the same time. The advantages of this method are that it allows tunnelling in one operation and is efficient. However, large mechanical equipment is required for large tunnels and this method is not suitable for unstable rock where large opening will induce significant stress on the rock mass.

4.6.2. Heading and Benching Method

In large tunnels and when the quality of the rock is not satisfactory, heading and benching method is often used. This method involves the driving the top portion of the tunnel in advance of the bottom portion. The lining of roof arch can then be constructed first by using the bottom bench as temporary supports. Another advantage of this method is that when cutting the bottom bench, the blasting becomes more effective by using vertical blast holes behind the tunnel face and less explosives can be used.

**Heading and benching method** (Peurifoy & Ledbetter)
### 4.6.3. Drift method

In very large tunnel or weak rock, the attacking of the tunnel face can be further subdivided into several stages. Similar to heading and benching, tunnelling is carried out in smaller section first and then widened subsequently.

Drift method can be further classified into centre drift, side drift, top drift and bottom drift.

Advantages of drift method:

a. Any zone of bad rock or excessive water will be discovered prior to driving the full bore, thus permitting corrective steps to be taken away.

b. The drift will assist in ventilating the tunnel during later operations.

c. The scale of each blasting is smaller hence vibration and damage are reduced.

d. Top and side drifts may facilitate the installation of support to the roof, especially for a tunnel driven through broken rock.
Disadvantages for drift method:

a. Small drift cannot accommodate large scale machine.
b. Jobs are divided into pieces such that the construction speed may be lowered.

4.9 New Austrian Tunnelling Method (NATM)

Traditional methods of tunnelling utilise the temporary or permanent works in taking up all the loadings from the soil or rock. The natural self-supporting properties of the ground is however being neglected, with the consequence of high cost for tunnel lining.

In New Austrian Tunnelling Method (NATM) a flexible lining is employed. It transforms the rock or soil surrounding the tunnel profile from a loading-exerting system into a load-carrying one. This is achieved through monitoring the behaviour of underground excavations and the revision of support to obtain the most stable and economical lining.

Methods of supporting tunnel roofs with rock bolts (Graham West)
NATM has been particularly successful in conditions where complex geological features which cause uncertainties in the prognosis of the rock mass behaviour are encountered.

The main features of NATM are:

a. **Flexible support**: The NATM is characterised by a flexible tunnel lining rather than a rigid one. The lining is form by a flexible combination of rockbolts, wire mesh, steel ribs and a thin layer of shotcrete. It is essential that the lining remains in full contact with the rock and both deflect together.

b. **Monitoring**: Sophisticated instrumentation is installed around the tunnel wall before the first shotcrete lining is placed. It is used to monitor the deformations of the excavation and the build-up of load in the support, so that the lining measures can be increased if necessary.
5. **Submerged Tunnel**

A submerged tunnel is a sub-aqueous tunnel constructed by the prefabrication of tunnel units and then submerged and jointed on the seabed. It is usually advantageous to construct submerged tunnel rather than bored tunnel below seabed because a cover of at least 10 m is required for the safe construction of a bored tunnel under seabed.

The first cross harbour tunnel in Hong Kong is made of steel but reinforced concrete ones are preferred now. Reinforced concrete tubes are not only cheaper than steel ones, but can be more easily made in rectangular cross sections, which were more suitable for multi-lane road tunnels. In addition, they can be constructed rather long to reduce the numbers of sinking and jointing operation.

The principal operations in construction of submerged tunnels are:

1. Initial fabrication
2. Trench preparation
3. Launching and sinking
4. Jointing
5. Sand jetting
6. Backfilling

5.1 **Initial Fabrication**

Tunnels units are pre-fabricated in a dry dock. The dry dock is usually an excavated basin beside seashore at a depth several meters below water level.

Besides the structural frame, fittings and accessories are installed onto the units. These include: lifting lugs, temporary support jacks, bearing plates & gaskets, ballast tanks, bulkheads, locating nibs, a control tower and a survey tower.
5.2 Trench preparation

While the tunnel units are pre-fabricated in the dry dock, a trench on the seabed for laying the tunnels units will be prepared at the same time. The trench may be excavated by dredging or by grabbing. The sides of the trench are usually sloped back to a stable angle.

To ensure the stability of the tunnel units on the seabed, the foundation of the tunnel units shall be prepared. There are two methods for the preparation of the foundation:

• Screeding method, and
• Sand jetting method

Screeding Method
Granular trench bedding materials are laid on the trench bed and then smoothed by a leveller.

Sand Jetting Method
Concrete pads are constructed at suitable locations on the trench bed for supporting hydraulic jacks. The tunnel bedding will be prepared by sand jetting method after the tunnel segment has been placed.
5.3 Launching and sinking

The open ends of the units will be closed with watertight temporary steel bulkheads to enable them to float. The floodgate of the casting basin is opened to let the seawater flowing in. The unit is then floated and towed to its final position.

The unit can be laid by fixed-leg platform, or more often nowadays by floating pontoons. In the later case, two pontoons are placed on top of the tunnel unit to be sunk. There are transit winches on the pontoons for adjusting the position of the pontoons. The wires from the winches are tied to heavy concrete block anchors on the seabed. The sinking operation starts with water ballasting of the
unit so that 2% negative buoyancy is established for sinking. Its position under water is carefully controlled by means of the surveying tower.

5.4 Jointing

At an end of each tunnel units, there are a bulkhead with a locating nib, and a Gina gasket or a steel bearing plate installed. The unit is lowered slowly until the locating nibs are engaged. Now the moving of the unit is taken over by hydraulic jacks.

The jacks pulled the newly sunk unit towards its neighbour until sufficient contact pressure is established between the Gina and the bearing plate. This initial compression provides an isolation of the water inside the gap from the outside.
Thereafter the water is discharged from the joint. The unbalanced hydrostatic pressure on the further end of the new unit will press the units tightly together.

The bulkheads at the joints are then removed. The waterproofing of the joint is further reinforced by installing an omega seal and covered with a steel plate by welding. Finally the joint is filled with concrete or cement grout.

### 5.5 Sand Jetting

If the tunnel bedding is placed by sand jetting, the sand and water are mixed and pumped down from a barge through deliver pipes to nozzles beneath the tunnel unit which are placed at 4 to 8 m intervals. Following the sand jetting bentonite/cement grout may be injected into the sand foundation for additional reinforcement.
5.6 Backfilling

Selected backfill comprising of granular material which will compact naturally under water is placed to mid-way of the tunnel depth.

General fill or granular fill material which would not cause damages to the tunnel waterproofing is placed on top until a cover of at least 2 m for the tunnel unit is attained.

Rock armour should also be provided near the shore for protection of tunnel from damages by vessels.