Guideline for Design of Road Tunnel

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Road Development Authority (RDA)
Japan International Cooperation Agency (JICA)
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1 Outline of Tunnel

1.1 Tunnel Definition

Tunnels are civil engineering structures that are constructed for the purpose of securing space in the ground. Depending on the purpose of use, tunnels are classified into road tunnel, railway tunnel and water way tunnel. In addition, in the case of Japan, tunnels are classified as mountain tunnels and city tunnels depending on the location conditions.

Tunnels generally refer to on-line structures in which a predetermined cross section is continuous in the longitudinal direction. Definition of the tunnel was given by the OECD (Economic Cooperation and Development Organization) Tunnel Recommendation Conference, OECD Advisory Conference on Tunneling in Washington 1970. The definition of tunnels is a cavity which is located below the ground surface and is used in some way and made into a prescribed geometry and has a size of two square meters or more.

1.2 Construction Method of Tunnels

In Japan, there are three kinds of general-purpose specifications for building tunnels. These are rock tunnel, shield tunnel, cut and cover tunnel. These construction methods are closely related to tunnel location conditions. For this reason, there is a tendency that the rock tunnel is selected for tunnels constructed in mountainous areas, and the shield tunnel or cut and cover tunnel is selected for city tunnels built on flat ground. However, depending on the topography and geological conditions, there are cases where the cut and cover method is adopted in portal of the mountain tunnel, and the rock tunnel is adopted in the urban tunnel. Hence, the boundary is not necessarily clear.

The Standard Specification for Tunneling for rock tunnel, shield tunnel, cut and cover tunnel is respectively developed by Japan Society of Civil Engineers. The target of this guideline is the rock tunnel.
Table 1-1  Construction Method of Tunnels (1)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mountain Tunnel</th>
<th>Shield Tunnel</th>
<th>Cut and Cover Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>• Suitable for consolidated bedrock, excavation is possible even in unconsolidated grounds by using</td>
<td>• Suitable for unconsolidated mountains / low consolidated mountains</td>
<td>• Mainly suitable for unconsolidated land, but it can be applied to any land</td>
</tr>
<tr>
<td></td>
<td>• Basics of excavation surface independence</td>
<td>• In the case of the closed type, it is possible to construct even if the excavation surface is not self-sustaining</td>
<td></td>
</tr>
<tr>
<td>Earth Covering</td>
<td>• Earth Covering more than 2D (tunnel outer diameter) is necessary. It is possible to construct even a few meters by using auxiliary method</td>
<td>• Earth Covering more than 1D (tunnel outer diameter) is necessary.</td>
<td>• Suitable for small earth covering (roughly 20 m or less)</td>
</tr>
<tr>
<td>Ground Water</td>
<td>• If the amount of spring water is large or the autonomy of the excavated surface can not be secured, an auxiliary construction method is necessary. It is necessary to consider the influence to the surroundings</td>
<td>• In the open type, countermeasures such as pressure method and underground water reduction method are required, but in the case of sealed type almost no auxiliary method is required</td>
<td>• It is necessary to take countermeasures such as groundwater reduction method and soil improvement</td>
</tr>
<tr>
<td>Location</td>
<td>• It is used in the mountains, but depending on ground conditions it is also used in urban areas</td>
<td>• It is also used in urban areas</td>
<td>• It is used in urban areas. Sometimes it is constructed as a start / arrival base of the shield Tunnel</td>
</tr>
</tbody>
</table>

(Source: JICA project)

Table 1-2  Construction Method of Tunnels (2)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mountain Tunnel</th>
<th>Shield Tunnel</th>
<th>Cut and Cover Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Condition</td>
<td>• horseshoe shaped cross section is used. An arbitrary sectional shape is possible to some extent, but an arch shape is desirable for the upper half</td>
<td>• determined by the cross sectional shape of the shield machine, but a circular cross section is used</td>
<td>• Generally, a rectangular cross section is used, but an arbitrary cross sectional shape is possible</td>
</tr>
<tr>
<td>Cross Section</td>
<td>• With the exception of special excavating machinery, it is impossible to change the cross sectional shape</td>
<td>• With special excavating machines, cross sections such as multi-circle and rectangle are also possible</td>
<td></td>
</tr>
<tr>
<td>Structure of Support and Lining</td>
<td>• Use steel support, rock bolts, shotcrete as support.</td>
<td>• Assemble a reinforced concrete made from a factory or a steel segment in the rear of the machine to make it the primary lining</td>
<td>• Rigid structure by steel frame or reinforced concrete is basic</td>
</tr>
<tr>
<td></td>
<td>• The lining is basically based on plain concrete by striking the place, but in the case where the ground pressure acts it may be a reinforced concrete structure</td>
<td>• In some cases lining is carried out with plain or reinforced concrete secondary lining</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Portal zone is generally arranged with reinforcing bars to prevent cracking due to shrinkage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: JICA project)
2 NATM in JAPAN

2.1 Difference between Conventional and NATM Method

NATM (New Austrian Tunneling Method) is one of the construction methods of tunnel proposed by the Austrian geologist Dr. Rabcewicz in 1964. NATM was introduced to Japan in 1977 in a railway tunnel, and since 1978 it became a standard construction method in railway tunnels. Also in the road tunnel, NATM was introduced in 1978 and became the standard construction method in Japan like the railroad tunnel.

NATM is quite different from the conventional method and it can be said that the construction method to make maximum use of the tolerance possessed by the ground because the support is in close contact with the ground. Figure 2-1 and Figure 2-2 show the difference between NATM and conventional method.
2.2 Concept of NATM in JAPAN
The fundamental difference of NATM from the conventional construction method is that
NATM shows the concept and necessary methods for tunnel design and construction by using
the strength of the ground as much as possible. Its basic philosophy is "to make the tunnel as
much as possible in the ground". In other words, it is the idea that the tunnel should be
retained as much as possible by the shear strength of the ground and the support is an
auxiliary structure aiming at reinforcing the ground.
2.3 Features of NATM in JAPAN

Characteristics of NATM in Japan are shown below.

a. The main support structure is the combination of shotcrete, rock bolt and steel support. The support structure is relatively thin and allows little displacement. This “soft” structure utilizes the strength of the ground to support the tunnel.

b. Quantitatively design is conducted based on statistical measurements such as ground pressure, supporting stress and deformation of the ground and support.

c. Since it is a relatively thin-walled support structure, resource-saving lining can be performed, which is advantageous for economy.

d. Since the support structure is flexible, it is possible to deal with even unstable rocks, and the degree of freedom of correspondence of the ground is high.

e. The surface of the support is smooth, the installation of the waterproof sheet becomes easy, and the structure with high waterer toughness can be constructed.

f. Since the inner space section is wide and can be effectively used, safety and work efficiency are improved. Also, it is easy to change the cross section.
3 Design of Tunnel (NATM in JAPAN)

3.1 Features of the Design of NATM

Since tunnels are on-line structures built underground, their design differs greatly from other structures. In general design of a structure, safety is evaluated according to the stress calculated by the structural calculation and the characteristics possessed by the material with assumption of an external force acting on the structure. In general, the construction method is examined to construct structures based on the design. On the other hand, in case of underground structures such as tunnels, it is difficult to correctly estimate the load acting on the tunnel in the design stage. Since the interaction between the ground and the support is complicated, the structural calculation is limited. Furthermore, it is difficult to provide sufficient information on geological survey methods and their accuracy to design; it is also difficult to design accurately over the entire length of the tunnel. Also, in the case of a tunnel, the behavior of the tunnel and the surrounding ground during excavation is different depending on the construction method. Therefore, the design of the support work must be done with due consideration of the construction method.

From technical background mentioned above, tunnel design and construction are usually carried out in the following procedure. In the initial design, designers make the best use of geological information and make an appropriate basic design. During the construction process, constructors collect and analyze the data of observation and measurement, and review the design to change to the support structure more suitable for the ground against the basic design.

In this way, it is vital to pursue the optimum construction method during constructing process.

3.2 Outline of Design Methods

3.2.1 Choice of Design Methods

The design of the tunnel is based on initial design (basic design) and tunnel design (basic design), which designs support structural members such as shotcrete, rock bolt, steel support and lining, based on limited ground survey results in advance. In the construction stage, modification of design is made to change the support structures based on the observation of the facing surface to be carried out at the time of excavation and measurement results and the like.

There are the following three types of design methods used in the initial design.

- Application of standard design
- Application of the design based on similar conditions
- Application of analytical design
However, in consideration of the design process and economic efficiency, each mountain grade, which distinguishes the ground mountain condition into several types, is set and the standard support pattern corresponding to it is often adopted in many cases.

3.2.2 Application of Standard Design

When standard cross sections are decided like roads and railway tunnels, general standard designs are used except for special conditions. In this method, representative support patterns for shotcrete, rock bolts, steel support, lining, etc. are set in advance for each class of grade and applied. The ground mountain grades are based on the geotechnical classification table evaluated by classifying the generation era of the mountain, the geological structure, the weathering / deterioration situation, the state of the discontinuous surface, the influence of the groundwater and the other geological conditions.

The geotechnical classification table and the standard support pattern are independently developed for each order because there is a close relationship with the each order size of the excavated cross section along with the construction method. In other words, a lot of construction result and observation data and also rock type, elastic wave exploration, rock quality condition, core condition, RQD (Rock Quality Designation), ground strength intensity ratio and situation at tunnel excavation are analyzed; then, the geotechnical classification tables and standard support patterns have been evaluated and set up.

Two examples of standard support patterns of road tunnels in Japan are shown in Table 3-1, Table 3-2 and Table 3-3. The first table is for general roads and the others are for expressways.
Table 3-1  A typical Example of Standard Support Pattern for Road Tunnels (Medium Section)

<table>
<thead>
<tr>
<th>Class of ground</th>
<th>Support pattern</th>
<th>Standard round length(m)</th>
<th>Spacing</th>
<th>Rock bolt</th>
<th>Steel Support</th>
<th>Thickness of shotcrete (cm)</th>
<th>Thickness of lining (cm)</th>
<th>The amount of allowable deformation (cm)</th>
<th>Excavation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>B B 2.0 3.0 1.5 2.0</td>
<td>Top heading, bench</td>
<td>Top heading, bench</td>
<td>H-125</td>
<td>10 30 (40) 0 0</td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C I C I 1.5 3.0 1.5 1.5</td>
<td>Top heading</td>
<td>Top heading</td>
<td>H-125</td>
<td>10 30 (40) 0 0</td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CII CE-a 1.2 3.0 1.5 1.2</td>
<td>Top heading, bench</td>
<td>Top heading, bench</td>
<td>H-125</td>
<td>10 30 (40) 0 0</td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D I DI-a 1.0 3.0 1.2 1.0</td>
<td>Top heading, bench</td>
<td>Top heading, bench</td>
<td>H-125</td>
<td>15 30 45 0</td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DII DII 1.0 or less 4.0 1.2 1.0 or less</td>
<td>Top heading, bench</td>
<td>Top heading, bench</td>
<td>H-150</td>
<td>20 30 50 10</td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1) As a general rule, the support pattern “h” is applied for class CII and DI ground, whereas application of support pattern “a” is considered when it is anticipated that the displacement induced by tunnel excavation is small and the face is stabilized.
2) On invert concrete:
   i) When the geology categorized as class CII and DI ground is Tertiary mudstone, clay, serpentinite or other rocks prone to argillation, or weathered crystalline schist or sedimentary clay, invert concrete, the thickness of which is given in parentheses, should be placed.
   ii) When early closure of excavation cross section is necessary, shotcrete is applied to the invert. The thickness of shotcrete in the invert should be determined, individually, referring to that in the top heading and bench. Although the thickness of shotcrete in the invert can be included in the thickness of invert concrete, the thickness of cast-in-place concrete in the invert should not be less than the thickness of lining in the arch and side wall.
   iii) Even if the class of ground is DI, the placement of invert concrete can be omitted in case the long-term bearing capacity of the ground is expected to be sufficient as a result of the appearance of sound rock in the invert, and squeezing due to lateral pressure is not anticipated.
3) On wire fabric:
   i) For class DI ground, wire fabric is generally placed in the top heading. For class DII ground, wire fabric is usually placed in both top heading and bench.
   ii) The placement of wire fabric can be omitted when steel fiber reinforced shotcrete (SFRC) is adopted.
4) On the amount of allowable deformation:
   For class DI ground, the amount of allowable deformation usually provided in the design is about 10 cm. The amount of allowable deformation is provided in the top heading for the bench cut method, whereas it is provided in both top heading and bench for full face method with auxiliary bench cut. The amount of allowable deformation should be modified from time to time based on the measurement results during construction.
5) For class A and E ground, specifications should be determined based on the actual ground conditions.
6) In the case where the design of ordinary section tunnels is applicable, the application of the support pattern for large section tunnels should be considered when the flattened cross section such as three center line area is adopted in the boundary region to large section.

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-65)
### Table 3-2  A typical Example of Standard Support Pattern for Expressway Tunnels (Medium Section)

<table>
<thead>
<tr>
<th>Class of ground</th>
<th>Support pattern</th>
<th>Standard round length(m)</th>
<th>Standard length(m)</th>
<th>Length(m)</th>
<th>Strength (kN)</th>
<th>Spacing</th>
<th>Area of installation</th>
<th>Top heading</th>
<th>Bench</th>
<th>Thickness of shotcrete (cm)</th>
<th>Thickness of lining (cm)</th>
<th>The amount of allowable deformation (cm)</th>
<th>Excavation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>B-a</td>
<td>2.0</td>
<td>3.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
<td>Top heading 120°</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>CI-a</td>
<td>1.5</td>
<td>3.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>Top heading</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>30</td>
<td>(40)</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>CI-b</td>
<td>1.2</td>
<td>3.0</td>
<td>1.2</td>
<td>Top heading</td>
<td>-</td>
<td>HH-100</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>30</td>
<td>(40)</td>
<td></td>
</tr>
<tr>
<td>DI</td>
<td>DI-a</td>
<td>1.0</td>
<td>4.0</td>
<td>1.2</td>
<td>1.0</td>
<td>Top heading</td>
<td>HH-108</td>
<td>HH-108</td>
<td>15</td>
<td>30</td>
<td>50</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>DI</td>
<td>DI-b</td>
<td>1.0</td>
<td>4.0</td>
<td>1.2</td>
<td>Top heading</td>
<td>-</td>
<td>HH-125</td>
<td>-</td>
<td>1.2</td>
<td>10</td>
<td></td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
</tr>
</tbody>
</table>

The classification of a and b of the support pattern is as follows:

- **a**: Basic support pattern applied to all basic rock types
- **b**: Applicable only in cases where it is expected that the displacements due to tunnel excavation are expected to increase in the initial design such as slate, black schist, 
  Invert's ( ) is applied to viscous rock such as Tertiary mudstone, tuff, serpentinite, weathered crystal schist, hot spring soil etc.


### Table 3-3  Former Typical Example of Standard Support Pattern for Expressway Tunnels (Medium Section)

<table>
<thead>
<tr>
<th>Class of ground</th>
<th>Support pattern</th>
<th>Standard round length(m)</th>
<th>Standard length(m)</th>
<th>Length(m)</th>
<th>Strength (kN)</th>
<th>Spacing</th>
<th>Area of installation</th>
<th>Top heading</th>
<th>Bench</th>
<th>Thickness of shotcrete (cm)</th>
<th>Thickness of lining (cm)</th>
<th>The amount of allowable deformation (cm)</th>
<th>Excavation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>B-a</td>
<td>2.0</td>
<td>3.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
<td>Top heading 120°</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>CI-a</td>
<td>1.5</td>
<td>3.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>Top heading</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>30</td>
<td>(40)</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>CI-b</td>
<td>1.2</td>
<td>3.0</td>
<td>1.2</td>
<td>Top heading</td>
<td>-</td>
<td>H-125</td>
<td>-</td>
<td>1.2</td>
<td>10</td>
<td></td>
<td>Full face method with auxiliary bench cut, or bench cut method</td>
<td></td>
</tr>
<tr>
<td>DI</td>
<td>DI-a</td>
<td>1.0</td>
<td>4.0</td>
<td>1.2</td>
<td>Top heading</td>
<td>-</td>
<td>H-125</td>
<td>1.0</td>
<td>15</td>
<td>30</td>
<td>45</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>DI</td>
<td>DI-b</td>
<td>1.0 or less</td>
<td>4.0</td>
<td>1.2</td>
<td>1.0</td>
<td>Top heading</td>
<td>H-150</td>
<td>HH-150</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

The classification of a and b of the support pattern is as follows:

- **a**: Basic support pattern applied to all basic rock types
- **b**: Applicable only in cases where it is expected that the displacements due to tunnel excavation are expected to increase in the initial design such as slate, black schist, 
  Invert's ( ) is applied to viscous rock such as Tertiary mudstone, tuff, serpentinite, weathered crystal schist, hot spring soil etc.

3.2.3 Application of the Design Based on Similar Conditions

If there is an existing tunnel in the proximity of the target tunnel and the construction result can be obtained, more reasonable initial design becomes possible by considering the actual results of the constructed tunnel. When designing the two close tunnels, measurement data of tunnels drilled at the beginning will be effective in designing the support pattern and construction method of the tunnel to be excavated later.

In cases that the ground conditions and design conditions, such as tunnel cross-section, are judged to be almost same, it is possible to apply the existing tunnel design to others after considering the similarity even if the existing tunnel is located far from the target tunnel. The point of view of similarity is shown in Table 3-4.

<table>
<thead>
<tr>
<th>Item</th>
<th>Focus Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function of tunnel</td>
<td>Are the functions of the tunnel the same?</td>
</tr>
<tr>
<td>class of ground</td>
<td>Is the Class of ground the same?</td>
</tr>
<tr>
<td>topography overburden</td>
<td>Are the topography and overburden similar?</td>
</tr>
<tr>
<td>property of ground</td>
<td>Whether rock species and geology ages, groundwater conditions, etc. are similar</td>
</tr>
<tr>
<td>Cross section shape and dimension</td>
<td>Cross section shape and dimension are similar?</td>
</tr>
<tr>
<td>Impact on surroundings</td>
<td>Whether the regulation values are similar</td>
</tr>
<tr>
<td>Proximity construction after completion</td>
<td>Type, positional relationship, scale, etc. are similar</td>
</tr>
</tbody>
</table>

(Source: JICA project)

3.2.4 Application of Analytical Methods

Tunnel design using analysis method is adopted for special tunnels (e.g. large cross-section tunnels and parallel tunnels), special mountains (e.g. unconsolidated land and expansive grounds) and special conditions (e.g. proximity to urban areas and existing structures).

Typical analysis methods are theoretical analysis method, FEM (Finite Element Method) analysis method, framework structure analysis, etc.

Design objects and their objectives for each analysis method are shown in Table 3-5.
(1) Theoretical Analysis Method
This method is based on elastic theory by continuum mechanics. Generally, detailed conditions can’t be reflected in this method because there are limitations on analysis conditions such as handling the tunnel as a circle and supporting structures being constructed simultaneously with the excavation. It is common practice to conduct a preliminary study of design by numerical analysis.

(2) FEM Analysis Method
This method is carried out for the purpose of examining the behavior of the mountain by grand designing the supporting structures. In this method, a complex stratum structure can be reproduced and handling of the construction process can be handled by expressing the ground within element model. In this analysis, two-dimensional analysis is often applied, but application examples of three-dimensional analysis are also increasing in recent years.
**Figure 3-1** Example of Two-dimensional FEM Analysis

(Source: Mountain tunnel construction method, from survey, design to construction, 2007, Japanese Geotechnical Society (in Japanese))

**Figure 3-2** Example of Mesh Diagram for 3D FEM Analysis

(Source: Mountain tunnel construction method, from survey, design to construction, 2007, Japanese Geotechnical Society (in Japanese))
(3) Framework Structure Method
In this method, a horseshoe-shaped tunnel cross section is modeled by a beam member pseudo-divided by a linear member; and the deformation of the tunnel due to the load is supported by the ground spring. Since it is relatively easy to handle, it is widely adopted in lining design.

Figure 3-3 Example of Framework Analysis
(Source: Mountain tunnel construction method, from survey, design to construction, 2007, Japanese Geotechnical Society (in Japanese))

3.3 Concept of Modified Design
3.3.1 Concept of Modified Design
Since the tunnel is a linear structure, it will encounter various geological structures. However, it is difficult to grasp in advance the characteristics of the ground in detail. Therefore, the initial design is only based on limited information. Then, the actual construction will modify the design as necessary while evaluating on-site measurement results etc. Hence, it is important to identify displacement and stress of ground, displacement and stress of the support with high accuracy during construction.

3.3.2 Concept of Modified Design in Construction
In the rock tunnel construction method, it is important to "make maximum use of the strength of the mountain without deteriorating it". Moreover, in order to stabilize by the interaction between the ground and the support, looseness occurs as shown in the figure, causing a change. The looseness occurs depending on the strength of the ground, the rigidity of the support and the installation time. For this reason, various surveys and measurements at the
time of construction are conducted. Moreover, the validity of the ground design and corresponding initial design are evaluated while confirming the behavior of the ground and the effect of the support accompanying the excavation by measuring etc. It is important to make corrections and promptly reflect on design and construction.

Figure 3-4  Conceptual Diagram of Ground and Support Characteristic Curve (Fenner-Pacher Curve)
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-58)

However, as shown in Figure 3-5, in general, the displacement amount obtained at the time of construction is about 60% of the total displacement amount; the influence of the excavation is about ± 1 D (D is excavation width), so it needs careful measurement management in this section.
It is very important to modify the original design / construction method to be suitable for the mountains in order to ensure the safety and economy of construction and to maintain long-term functions and quality of tunnel structures. The Table 3-6 shows the items of survey and measurement under construction and the evaluation of the results.
### Table 3-6  Items of Survey and Measurement under Construction and Evaluation of Results.

<table>
<thead>
<tr>
<th>Investigation and Measurement</th>
<th>Detail Item</th>
<th>Evaluation of Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Strength</td>
<td>Drilling Speed</td>
<td>Confirm ground condition</td>
</tr>
<tr>
<td></td>
<td>Using Explosive amounts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Excavation speed (/day)</td>
<td></td>
</tr>
<tr>
<td>Face Conditions</td>
<td>Rock Type, Rock Quality, Cracking condition</td>
<td>Confirm ground condition</td>
</tr>
<tr>
<td></td>
<td>Reacon density , Strike , Tipping</td>
<td></td>
</tr>
<tr>
<td>Water Inflow</td>
<td>Water inflow in face, water pressure in face</td>
<td>Confirm water inflow</td>
</tr>
<tr>
<td></td>
<td>Drainage Condition</td>
<td></td>
</tr>
<tr>
<td>Measurement A</td>
<td>Crown Settlement, Convergence</td>
<td>Grasp ground action and support stability</td>
</tr>
<tr>
<td></td>
<td>Convergence situation of displacement</td>
<td></td>
</tr>
<tr>
<td>Measurement B</td>
<td>Geographical situation around tunnel excavation</td>
<td>Grasp ground action and support stability</td>
</tr>
<tr>
<td>Influence of proximity</td>
<td>Behavior of ground surface, ground and surrounding structures</td>
<td>Grasp influence of proximity structure and ground surface</td>
</tr>
<tr>
<td>Construction</td>
<td>Behavior of portal</td>
<td></td>
</tr>
<tr>
<td>Weather Condition</td>
<td>Weather, Temperature, amount of rainfall, earthquake</td>
<td>Estimate damage condition</td>
</tr>
<tr>
<td>Ground water at Surrounding</td>
<td>River flow, Ground water level</td>
<td>Grasp influence of excavation</td>
</tr>
<tr>
<td>Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work environment in a Tunnel</td>
<td>Temperature, humidity, oxygen concentration</td>
<td>Grasp site environment</td>
</tr>
<tr>
<td></td>
<td>Ventilation mounts, Dust concentration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inflammable gas and Methane, poisonous gas concentration</td>
<td></td>
</tr>
<tr>
<td>Environment at Surrounding</td>
<td>Noise, vibration, low frequency sound, drainage concentration</td>
<td>Grasp environment surrounding area</td>
</tr>
<tr>
<td>Area</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: JICA project)

In some case, the large deformation of the ground and a change in support structures occurs even if the construction is carried out as designed. In that case, consideration of countermeasure work is required. The main countermeasures are listed below.

a. Size of support  
b. Reinforcing of face and face forward ground  
c. Changing of the buckwheat breakage, construction law (change of bench length, installation of invert, etc.)  
d. Early launch of concrete  
e. Securing or expanding deformation allowance

### 3.3.3 Concept of Modifying Design of Future Section

In the design of future sections, the following four cases are assumed from the situation at the time of construction.
a. The tunnel is stabilized by the supporting members and construction method as
designed, and the amount of displacement is also within the assumption.
b. The tunnel is stable at a position less than the assumed amount of displacement
c. Supplementing the support and changing the construction method are required to
suppress to the assumed amount of displacement.
d. A displacement which is greatly larger than the assumed amount of displacement
occurs, and as a result, it is impossible to secure the cross section, which leads a
substantial increase in the supporting structure and a significant change in the
construction method.

The countermeasures of the four cases mentioned above are described below.

(1) “Tunnel stabilized by supporting members and construction method as designed”
Since it is judged that design and construction are mostly conforming to the target ground,
it can be judged that there will be no problem in future sections by construction as
designed.
However, from the economic point of view, if there is a possibility of mitigating support
structures, it is desirable to consider reducing the size of the support by analyzing the
results of the measurement work.

(2) “The tunnel is stable but displacement is small”
The ground is better than what was assumed at initial design. There was a possibility that
the designed supporting members and construction methods were excessive.
Therefore, it is necessary to consider reduction of supporting members and change of
support patterns. However, there are also cases where the ground changes suddenly, so it
is important to formulate a detailed measurement tool as well as possible.

(3) “Changing support pattern and construction method to reduce displacement amount
required”
Study of the auxiliary construction method is necessary when it is confirmed that the
construction method as designed is implemented and that the support is installed at the
appropriate time and there is no problem in construction.
However, it is necessary to carefully examine the workability and economic efficiency as
to whether the change of the support pattern is good or the addition of the auxiliary
construction method is good. After the examination, it is necessary to make a modified
design.
(4) “Changing major support and construction method to reduce displacement amount required”

Drastic review and modification of design and construction method are required. Based on the measurement results, it is necessary to investigate optimum support and construction method using analytical methods and the like. It is also necessary to study examples of similar ground conditions.
3.4 Detail of Design Method

3.4.1 Flow of Design

A flow of tunnel design is shown Figure 3-7.

![Flow of Tunnel Design](Image)

Figure 3-7  Flow of Tunnel Design
(Source: JICA project)
3.4.2 Design Condition

(1) Ground Conditions
Since the rock tunnel is a structure that utilizes the support function of the ground, it must be designed considering the geographical conditions consisting of topography, geology and hydrology. Also, when considering geotechnical conditions, the strength and deformation characteristics of the ground, the stability of the face and the geological characteristics such as spring water must be considered.

(2) Location Requirement
In designing the tunnel, the impacts of tunnel construction on surrounding environment should be considered. Furthermore, the impacts of nearby constructions and special tunnel position should be also considered. Regarding the surrounding environment at tunnel construction, it is necessary to pay attention to the following points.

a. Noise and vibration of blasting, noise caused by construction vehicles, vibration and traffic problems
b. Water pollution such as groundwater and river water by excavated shear and construction wastewater
c. Drought and ground subsidence around the tunnel
d. Contamination and uplift of groundwater by injection of chemical liquid etc.
e. Impact of excavation on ground surface and nearby underground structures

On the other hand, the influence on the surrounding environment after construction can be considered as follows.

a. Drought phenomenon of rivers and wells due to change of groundwater environment
b. Ground surface subsidence due to loosened ground and lower groundwater
c. Changes in water quality of long-term groundwater by injection of chemical liquid etc.
d. Traffic vibration and noise
e. Effects of the portal area on the surrounding environment

(3) Shape and Dimensions
When designing the cross section, it is necessary to consider the shape and dimensions of the tunnel determined from the purpose and form of use.

NATM has a high degree of freedom with respect to shape and size, and it is possible to
construct tunnels of various shapes and dimensions as long as the ground, support, and lining have the ability to hold space. That is one of the strong point of NATM.

The cross section includes a predetermined construction gauge, required facilities, allowance etc., and taking safety and economics into consideration.

In addition to the construction gauge, the road tunnel is determined taking into consideration construction limitations, ventilation, lighting, emergency facilities, interior wall, passage for management, installation space for pavement (overlay), drainage, and allowance for construction error of lining.

(4) Conditions for Taking Action of External Force into Consideration
When designing a tunnel, the influences of earth pressure, water pressure, earthquake, etc., which act after tunnel completion, should be considered as necessary.

Earth pressure is categorized as plastic pressure, loose earth pressure and unbalanced earth pressure. When these earth pressure effects are assumed, it is necessary to consider them in the design.

Water pressure has external water pressure and internal water pressure, and it is necessary to consider in the design when it is assumed that they act. As for earthquakes, since the tunnel behaves together with the surrounding land, the influence of earthquake is small compared with other structures. However, from the damage case of the major earthquake in Japan, attention should be paid in the following cases at the time of design considering the influence of the earthquake.

a. Earth covering of Tunnel is small and the tunnel exists in unconsolidated mountains
b. The tunnel exists in the geological failure section
c. Tunnel intersects an active fault

3.4.3 Cross Section
The method of determining the cross section in Japan is introduced the following section.

The cross section of the tunnel includes the construction gauge prescribed by the Road Structure Order and the necessary allowance, and it is decided in consideration of the safety and economy of the tunnel and the running performance of the vehicle. In addition, it is necessary to secure a space for installing ventilation facilities, lighting facilities, emergency facilities, interior management passage, pavement and drainage. In addition, a cross section
should include allowance for construction error of lining. Thus, the elements determining the inner space section are as follows.

a. Road specifications and cross road construction  
b. Allowance of construction gauge and tunnel cross section  
c. Presence or absence of ventilation equipment  
d. Presence of interior board  
e. Pavement composition  

In consideration of safety and economic efficiency, the cross section of the tunnel is usually a horseshoe shape consisting of a top heading triangle (top heading semicircle) or a flat cross section such as a fifth centered circle.

In the case of using Tunnel Boring Machine (TBM), there are many cases of circular cross sections in general.
(1) Representative Japanese Road Tunnel Cross Section

Representative Japanese road tunnel cross section is shown in Figure 3-9.

Figure 3-9  Example of Standard Japanese Tunnel Section
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-11)
(2) Flow of Determination of Road Tunnel Cross Section

Flow of determination of road tunnel cross section is shown in Figure 3-10. In Sri Lanka, some tunnel design condition is not decided at present. Therefore, it is necessary to examine the gradient (slope) of the pavement, the structure of the pavement, the shape of the drainage, the decision on the need for parking zone and others, to determine the final cross section. Moreover, it is necessary to examine the cross-section from view point of economic efficiency and consistency among the tunnels located near the target tunnel.

Figure 3-10  Flow of determination of Road Tunnel Cross Section
(Source: JICA project)
3.4.4 Design of Portal Zones and Portals

(1) Points to Note when Designing the Portal Zone

Portal zones are the areas near the tunnel entrance and exit where the overburden is generally small and a ground arch is not formed easily. Portals are frequently located in a generally weak geologic zone where erosion develops and complicated topography is created. While the tunnel is in service, portals are susceptible to natural and meteorological disasters such as rock falls, avalanches, debris flows and earthquake. Portals sometimes may be subjected to overburdened loads or earth pressure after being placed into service. Therefore during the design of the portal zone and portals, the engineer must decide on an appropriate portal structure construction method, portal forms, portal shapes, and the portal structures by giving sufficient consideration to natural conditions such as the topographic features, geology, groundwater and weather in the vicinity of the portals and socially restrictive conditions including the presence or absence of homes and structures.

Table 3-7 and Table 3-8 list problems expected mainly during the construction of a tunnel portal zone and design conditions. The portal zone is generally defined as an area where the depth of overburden is one to two times the excavation diameter where development of the ground arch is difficult, as shown in Figure 3-11.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope failure or landslide</td>
<td>Construction in the portal zone sometimes induces a slope failure or landslide. This can be attributed to loosening because of tunnel excavation or slope cut for the construction of the portal. When there is a possibility of a slope failure or landslide because of tunnel excavation, measures should be taken to protect the slope in advance of the excavation.</td>
</tr>
<tr>
<td>Unsymmetrical pressure</td>
<td>Unsymmetrical pressure may act on the tunnel section and a large stress may occur in the tunnel depending on the positions and relationship of the slope and tunnel. Unless the tunnel is stable, measures are required to balance the earth pressure by using a counter-weight fill or cut for slope stabilization.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-112)
Table 3-8 Problems Expected in Tunnel Portal Zone and Design Considerations (2)

<table>
<thead>
<tr>
<th>Issue</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient bearing capacity of ground</td>
<td>In the portal zone, where the depth of overburden is small, the total load over the tunnel sometimes may act on the tunnel. Because the ground in the portal zone consists of unconsolidated deposits or is in a weathered zone, the base often suffers from settlement or deformation because of the insufficient bearing capacity of the ground. Design of the portal zone including the construction method must be decided so the required bearing capacity of the ground can be obtained.</td>
</tr>
<tr>
<td>Face collapse</td>
<td>In the portal zone, the ground is often weak and poorly consolidated. Even when the ground consists of hard rocks, faults or fracture zones may induce the development of fractures and the stability of the face frequently will be poor. When the face cannot be expected to stand for an adequate length of time, an excavation method or auxiliary method to prevent face collapse must be studied.</td>
</tr>
<tr>
<td>Ground surface settlement</td>
<td>In the portal zone, small overburden, insufficient bearing capacity of the ground and insufficient stand-up time at the face might cause the impact of settlement to be conveyed to the ground surface. When there are ground level structures for which settlement must be restricted, adequate measures must be taken to prevent problems and an auxiliary method must be adopted whenever required.</td>
</tr>
<tr>
<td>Rock falls, debris flow or avalanches</td>
<td>The portal zone must be designed for a location free from rock falls, debris flows or avalanches. When such positioning of the portal is impossible, adequate measures should be taken against possible disasters.</td>
</tr>
<tr>
<td>Neighboring structures</td>
<td>The impact of tunneling construction on existing structures in the neighborhood such as houses, steel towers, roads and railways, and the effect of noise and exhaust gas after the tunnel is placed into service, also should be studied.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-113)

Figure 3-11 Area of Standard Portal Zone

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-113)
(2) Support of Portal zones
Since the soil covering is small in the portal zones, the arch action does not work. Hence, uneven ground pressure acts as a load on the support structure. From this, it is necessary to stabilize it with a rigid support.

(3) Lining of Portal Zones
Considering the drying shrinkage of concrete, the influence of earth pressure, and the influence of earthquake, the lining generally has a reinforcing bar structure. Normally, the main reinforcement is set to D19 mm or more, and the force distributing bar is set to D16 mm or more, and it is set as a single rebar.

(4) Design of Portals
The structures at tunnel portal protect the portal zone from landslide, rock falls and avalanches down the slope’s surface, and require a mechanically stable design. The external appearance and shape of the portal should be determined according to the use of the tunnel and in order to preserve compatibility with surrounding natural environment and landscape. When determining the location and the type of the portal, the following conditions shall be...
studied comprehensively.

- **Topographic and geologic conditions**
  (bearing capacity of lower portion of the portal, stability of the surface behind the slope, presence of unbalanced earth pressure, possibility of landsides or rock falls, positional relative to swamps and valleys)

- **Meteorological conditions**
  (snow, snowfall, snow cornices, drifting snow, avalanches)

- **Portal location during construction**
- **Environmental conditions**
  (land use conditions, extent of changes in surrounding environment and landscape in the surrounding area)

- **Coordination with plans for the vicinity**
  (tie-in with open sections such as bridges, relationship with relocated roads, shifting channels, location of planned future maintenance management facilities near the portal)

- **Economic efficiency**
- **Others (direction of incident sun light etc.)**

Portal forms are classified as either wall type or protruding type. Characteristics of the general types of portals are shown in Table 3-9.
### Table 3-9: Types and Characteristics of Tunnel Portals

<table>
<thead>
<tr>
<th>Type</th>
<th>Wall type</th>
<th>Promoting type</th>
<th>Promoting type</th>
<th>Promoting type</th>
<th>Promoting type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gravity/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Semi-gravity type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wing type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arch wing type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parapet type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Promoting type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bell mouth type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inverted bell mouth type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Overview
- Gravity type retaining wall placed about 10m forward of the portal position. Recently replaced by wing type and now is seldom adopted.

#### Ground conditions appropriate for application
- Comparatively steep topographic features or where a structure like an earth retaining wall is required.
- Where rock falls are expected.

#### Meteorologic conditions appropriate for application
- Few problems even when used in snowy areas.

#### Points to note for design and construction
- Integration of the portal into the tunnel is required.

#### Landscape
- Inclination of weight and pressure can be mitigated by the arch section curve.
- Must consider compatibility with the surrounding topographic features.

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-118)
3.4.5 Shotcrete

(1) Conception of Function and Effects

Shotcrete concrete is the most important supporting member that does not loosen the ground because it can be installed in any shape immediately after excavation of the tunnel, and it comes into close contact with the ground. The support function of shotcrete is thought to be its resistance to the deformation of bedrock which accompanies boring, and the compaction and shear resulting from external forces. These functions of shotcrete provide effective support in various combinations, and stabilize bedrock.

Various concepts of these functions and effects as tunnel support can be considered together with conceptual diagrams as given in Table 3-10 and Table 3-11. It is necessary to decide specifications for thickness, strength, and other design values of shotcrete taking into consideration bedrock conditions, the purpose of the tunnel and other conditions, in order to ensure the stability of the tunnel after boring.

Table 3-10  Concepts of the Function and Effect of Shotcrete (1)

<table>
<thead>
<tr>
<th>Category of function, effect</th>
<th>Summary of function and expected effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>I axil compaction</td>
<td>Resisting comparatively uniform external forces mainly against the internal space creating the arch, and resisting the axial forces which cause deformation, using the axial compaction resistance and rigidity of concrete.</td>
</tr>
<tr>
<td>II shear resistance of</td>
<td>Resisting shear force and shear displacement which causes localized ejection, using the shear resistance and rigidity of concrete. Adhesion between the bedrock and shotcrete is necessary. If adhesion is lost, concrete goes into flex resistance mode.</td>
</tr>
<tr>
<td>III flex resistance of</td>
<td>Resisting flexing moment which causes localized ejection, using the flex resistance and rigidity of concrete.</td>
</tr>
<tr>
<td>IV shear resistance,</td>
<td>Support of loads taken by I to III above, and distribution of that support function over the bedrock, using the shear resistance (adhesion resistance) at the shotcrete - bedrock interface.</td>
</tr>
<tr>
<td>adhesion resistance of</td>
<td>bedrock interface</td>
</tr>
<tr>
<td>concrete - bedrock interface</td>
<td></td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-72)
### Table 3-11  Concepts of the Function and Effect of Shotcrete (2)

<table>
<thead>
<tr>
<th></th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rock fall prevention, retaining of small rock masses</td>
</tr>
<tr>
<td></td>
<td>Work safety is ensured by protecting small rock masses separated by the surfaces of discontinuity which are about to fall from the tunnel face immediately after boring due to action of gravity; prevents carelessness that can result in repeated rock collapse</td>
</tr>
<tr>
<td>2</td>
<td>application of internal pressure to bedrock</td>
</tr>
<tr>
<td></td>
<td>In soft bedrock or sedimentary bedrock tunnels where poral deformation is pronounced, shotcrete, as a reaction force, provides the bedrock with radial outward binding force, and by preserving the triaxial conditions of the bedrock in the vicinity of the tunnel boring face, increases the load bearing capacity of the bedrock.</td>
</tr>
<tr>
<td>3</td>
<td>reinforcement of weak strata and protection of shape</td>
</tr>
<tr>
<td></td>
<td>At weaknesses in the bedrock, such as open fissures and weak strata, plug reinforcement with shotcrete, or fusing or integrating parts of the bedrock which are comparatively strong straddling the weaknesses, reduces the effects of surfaces of discontinuity and weak strata within the bedrock.</td>
</tr>
<tr>
<td>4</td>
<td>leveling out of stress distribution</td>
</tr>
<tr>
<td></td>
<td>By plugging crevices, and finishing the spray surface in a smooth arc, circumferential stress distribution in the shotcrete and bedrock is leveled out. Further, the support effect of rock bolts and steel tunnel supports arranged locally is enlarged and transmitted over the surface, and tunnel biased loads, localized loads appearing in the tunnel are supported and distributed over the surface.</td>
</tr>
<tr>
<td>5</td>
<td>protective covering, prevention of degradation of bedrock</td>
</tr>
<tr>
<td></td>
<td>Provides a protective covering of the boring bedrock surface, and prevents the degradation of bedrock by dehydration or oxidation through contact with air, and softening of bedrock and outward flow of soil particles through contact with water inflow.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-72)

The mechanical characteristics of shotcrete shall be determined taking into account the expected function, effect and bedrock conditions. In general, comparatively high compaction strength is commonly required in the initial stage after application for shotcrete used in tunnels. Required typical strength settings one day after application are as follows,

- Two lane road tunnel one day strength of 5N/mm²
- Bullet tunnel (shinkansen) one day strength of 8 N/mm²
- Large cross section road tunnel one day strength of 10N/mm²

Design standard strength is generally defined as uniaxial compaction strength 28 days after application, i.e. long-term strength, set at 18N/mm² for a two lane road tunnel and a railway tunnel. On the other hand, higher strength of 36N/mm² may be set for large cross section road tunnels, to reduce thickness of spraying and to increase resistance with the expansive bedrock.
(3) Mix of Shotcrete

Mix of Shotcrete shall be determined taking into consideration qualities such as required strength and constraints on construction, as well as design standard strength and related strengths together with variation in concrete strength which occurs on the side. In planning the mix of shotcrete, it is important to take into consideration constraints on construction in addition to qualities such as strength. The main items to consider in shotcrete mix are as follows:

a. Strength (initial stage strength, early stage strength, long-term strength)
b. Adhesion
c. Compactness (adsorbed moisture, void volume, permeability and others)
d. Durability (freeze/thaw resistance, chemical resistance, carbonation resistance)
e. Rebound ratio
f. Volume of dust produced

Since strength of shotcrete depends on the spraying method, water inflow conditions of the sprayed face, portal air temperature, humidity, water/cement ratio or water/bonding, material ratio, fine aggregate ratio, maximum dimensions of coarse aggregate and other materials used, it is essential that the characteristics of these materials must be considered and ingredients should be selected appropriately. Examples of specified mixes used in a road tunnel are shown in Table 3-12.

<table>
<thead>
<tr>
<th>Road</th>
<th>Maximum dimensions of coarse aggregate Gmax(mm)</th>
<th>slump (cm)</th>
<th>Cement C (kg)</th>
<th>Accelerating agent C × %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>Normal mix</td>
<td>15</td>
<td>360</td>
<td>5.5</td>
</tr>
<tr>
<td>Dry method</td>
<td></td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal mix</td>
<td>Wet method</td>
<td>15</td>
<td>8</td>
<td>5.5</td>
</tr>
<tr>
<td>high strength</td>
<td></td>
<td>10</td>
<td>450</td>
<td>10.0</td>
</tr>
<tr>
<td>standard mix</td>
<td></td>
<td>15</td>
<td>18 ± 2</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Source: JICA project)
(4) Reinforced Shotcrete

In case that reinforced is necessary in shotcrete, the strength characteristics of shotcrete materials should be improved, or the sprayed thickness should be increased. Of these two methods, the strength characteristics of shotcrete materials can be improved by reinforcement with wire nets or fibers to improve shear strength, tensile strength and toughness in addition to increasing compaction strength.

1) Wire netting

Wire netting is used to improve the shear reinforcement of shotcrete to prevent peeling at and after time of application and to improve toughness after the appearance of cracks. In bedrock which shows a large degree of deformation such as expansive bedrock, many cracks may form in shotcrete. Furthermore, lumps of concrete may peel. In this case, it is common to use wire netting to improve peeling and toughness. On the other hand, where there are many joints and fissures in hard rock with concern that rock masses might collapse suddenly, wire netting is commonly used to reinforce the shear strength and to improve toughness of shotcrete. Welded wire netting is generally used commonly with a mesh of $100 \times 100$mm or $150 \times 150$mm and wire diameter of about 3.2 to 6.0mm.

2) Fiber reinforcement

Fiber reinforced shotcrete may be effectively used in places where deformation is large and toughness is necessary, or places where the stress distribution of tunnel support is complex, and toughness and flex resistance is necessary.

The examples of mixes for fiber reinforced shotcrete are shown in Table 3-13.

Table 3-13  Examples of Fiber Reinforcement Mix

<table>
<thead>
<tr>
<th>$\sigma_{28,N/mm^2}$</th>
<th>units</th>
<th>$kg/m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement C</td>
<td>water W</td>
<td>fine aggregate S</td>
</tr>
<tr>
<td>36</td>
<td>450</td>
<td>202.5</td>
</tr>
</tbody>
</table>

(b) Vinylon fiber reinforced shotcrete mix in the Tohoku bullet train Iwate tunnel Mega dept.

<table>
<thead>
<tr>
<th>fine aggregate ratio S/a %</th>
<th>cement C kg/m³</th>
<th>silica fume %</th>
<th>accelerating agent %</th>
<th>vinylon fiber kg</th>
<th>wetting agent %</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>360</td>
<td>5</td>
<td>5.5</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-80)
3.4.6 Rock Bolt

(1) Conception of Function and Effects of Rock Bolt

Rock bolt is made up of plates and nuts for fixing to the sprayed concrete, and reinforcing bars inserted in the drilled holes. As opposed to shotcrete and steel tunnel supports, the characteristics of rock bolts is that rock bolts have a support function from inside of the bedrock. It is thought that the support function of rock bolts is mainly to suppress relative displacement parallel to or at right angles to the fissure plane in the case of medium hard and hard bedrock which has developed fissures, and to suppress relative displacement in a direction radial to the tunnel between the tunnel wall surface and the bedrock in the case of soft bedrock and sedimentary bedrock. These functions and effects of rock bolts as tunnel supports are shown in Table 3-14. Further, the relationship between bedrock conditions and function and effect of rock bolts is shown in Table 3-14.

In planning rock bolts, it is necessary to decide the specification of the anchorage system, anchorage material, distribution and dimensions, material and shape, taking into consideration geologic structure and the relationship to the function and effects of rock bolts, bedrock conditions, the aim of the tunnel, and constraints on construction, in order to ensure the stability of the tunnel after excavation.
Table 3-14  Concepts of Function and Effects of Rock Bolts

<table>
<thead>
<tr>
<th>Category of function, effect</th>
<th>Summary of function and expected effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Function to suppress displacement relative to bedrock in the axial direction, by the tensile resistance of the rock bolt in that direction</td>
</tr>
<tr>
<td>II</td>
<td>Function to suppress displacement relative to bedrock at right angles to axial direction, by the shear resistance of the rock bolt in that direction</td>
</tr>
<tr>
<td>Function of Rock Bolt</td>
<td></td>
</tr>
<tr>
<td>tense resistance of rock bolt</td>
<td>In medium hard bedrock and hard bedrock, which has developed fissures, binds unstable masses of rock partitioned by fissures to deep bedrock, and inhibits the peeling and ejection of those masses of rock.</td>
</tr>
<tr>
<td>shear resistance of rock bolt</td>
<td></td>
</tr>
<tr>
<td>a: suspension effect</td>
<td>In medium hard bedrock and hard bedrock, if rock bolts are placed to intersect with fissures, shear strength of the fissure plane is increased, and the apparent effect of improvement to the nature of the bedrock can be expected. Also, in the case of soft bedrock or sedimentary bedrock with little strength, depending on placement of rock bolts, the improvement of shear resistance of bedrock, and of residual strength after yield, and the apparent effect of improvement to the nature of the bedrock can be expected.</td>
</tr>
<tr>
<td>b: stitch effect</td>
<td></td>
</tr>
<tr>
<td>c: effect of improvement to the nature of the bedrock</td>
<td>In the case of soft bedrock or sedimentary bedrock, the axial forces developed by the rock bolt act on the shaft wall through the medium of the shotcrete, demonstrating an apparent internal pressure, and the suppression of plasticization of bedrock surrounding the tunnel and its extension can be expected.</td>
</tr>
<tr>
<td>Effect</td>
<td></td>
</tr>
<tr>
<td>1) Reinforcement effect of bedrock</td>
<td>Rock fragments smaller than the placement interval of rock bolts, which have separated from the bedrock, are supported by shotcrete. Shotcrete supports the load by adhesion to the bedrock. However where adhesion between the shotcrete and the bedrock is lost, by stitching the shotcrete to the bedrock, rock bolts can be expected to support that load.</td>
</tr>
<tr>
<td>2) internal pressure effect</td>
<td></td>
</tr>
<tr>
<td>3) Shotcrete support effect</td>
<td></td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-82)
Table 3-15 Relationship between Bedrock Conditions and Function and Effect of Rock Bolts

<table>
<thead>
<tr>
<th>Bedrock conditions</th>
<th>Support function</th>
<th>Axial tensile resistance (perpendicular rigidity and strength)</th>
<th>Shear resistance at right angle to axis (shear rigidity and strength)</th>
<th>Discontinues</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rock, medium hard rock</td>
<td>Suspension effect</td>
<td>Internal pressure effect</td>
<td>Spray support effect</td>
<td>Effect of improvement to the tunnels of the bedrock</td>
<td></td>
</tr>
</tbody>
</table>

Reference
2) Japan Society of Civil Engineers Rock Mechanical Committee-rock bolt design WG: No.30 Rock mechanical symposium, pp.393-401, 2000.

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-83)

(2) Rock bolt Anchorage System

The common rock bolt anchorage system is the complete anchorage systems which fixes the whole length of the rock bolt to the ground. There are two types of complete anchorage systems depending on the rock bolt anchorage method: anchorage material type and friction type. They are categorized based on structure and type of anchorage material as explained in Figure 3-14. The characteristics and limits of use for both methods are explained in Table 3-16.

Figure 3-14 Classification of Rock Bolts for Complete Anchorage Systems

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-84)
(3) Distribution and Dimensions of Rock Bolts

Distribution of rock bolts is decided taking into consideration bedrock conditions, size of tunnel cross section, shape, drilling method, constraints on construction and other conditions. In principle, it is best to distribute rock bolts for support to efficiently reinforce those areas affected by tunnel drilling.

However, distribution is normally decided using a systematic arrangement of bolts which is a tried and tested standard support pattern chosen on the basis of the determined bedrock classification taking into consideration bedrock conditions.
The dimensions of the lock bolt are generally based on about 2 to 4 m. In addition, those whose diameter is about 22 to 25 mm are used. Examples of distribution of rock bolts based on differing bedrock conditions are shown in Figure 3-15.

![Figure 3-15 Examples of Distribution of Rock Bolts in the Tunnel Transecting Direction](Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-89)

### 3.4.7 Steel Supports

(1) Conception of Function and Effects of Steel Supports

Since steel supports, which are arch shaped reinforcements fitted against excavated tunnel surfaces, should take effect as soon as they are installed, they contribute to stabilizing the excavated tunnel face until the strength of shotcrete is fully developed. Steel supports also make easier stabilization of the tunnel by combining with shotcrete. The function and effect of steel supports are shown in Table 3-17.
Table 3-17  Concept of Function and Effect of Steel Supports

<table>
<thead>
<tr>
<th>Function or Effect</th>
<th>Description of function and obtainable effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Similar to shotcrete, steel supports can resist external forces with compressive resistance, shear resistance and bending resistance. Those functions are effective immediately after installation. When the shotcrete reaches an effective strength, the resistance supplied by the steel supports unites with the shotcrete.</td>
</tr>
<tr>
<td>1) Support of rock mass</td>
<td>Steel supports can be tightly attached to the tunnel to prevent spalling of partial rock blocks due to bending or shear resistance.</td>
</tr>
<tr>
<td>2) Reinforcement of weak ground</td>
<td>Steel supports can reduce the effect of discontinuities and weak layers by supporting cracks and openings or small-scale weak layer.</td>
</tr>
<tr>
<td>3) Utilization of inner pressure toward the ground</td>
<td>Steel supports can provide inner pressures along the tunnel wall in the radial direction for weak ground that cannot be expected to form a ground arch. This allows confined stress state that increases load carrying capacity of entire ground.</td>
</tr>
<tr>
<td>4) Reinforcement of shotcrete</td>
<td>Steel supports fuse with the shotcrete to improve the stiffness and toughness of shotcrete particularly at early age of shotcrete with low elastic modulus and strength. In addition, after appearance of sufficient strength in the shotcrete, steel supports can be integrated into the shotcrete and applied tightly on the tunnel wall to form an arch shell structure and then stabilize the tunnel and the surroundings.</td>
</tr>
<tr>
<td>5) Transfer of loads to ground (footing)</td>
<td>Steel supports can transfer the loads from the surroundings to the foundation through the wing ribs.</td>
</tr>
<tr>
<td>6) Support for forepoling</td>
<td>Steel supports can function as the reaction point for the forepoling supporting the ground ahead of the tunnel face and restrain the failure or loosen of surrounding ground.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-93)

(2) Shape of Steel Supports

Steel supports should be designed properly to support the strength transferred through the shotcrete with a yield bending moment as small as possible in a shape similar to the excavated section. The shape of steel supports includes top heading, upper and lower halves, and all surrounding as shown in Figure 3-16. Also the shape of steel supports is determined based on the nature of surrounding ground, intensity and direction of applied strength, and
method of installation.

![Figure 3-16 Various Shapes of Steel Support](Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-93)

(3) Steel Support Material

The steel used for steel supports usually includes H-beams, U-beams, circular pipes, and lattice girders. Currently H-beams are most frequently used. Parameters of steel products for steel supports in Japan are shown in Table 3-18.

(4) Joints and Base Plates for Steel Supports

Since the joints of the steel supports may become a structural weak point of the support members, it is necessary to design joint positions and connected mechanisms considering the excavation shape as well as the size and distribution of the resulting stress. Figure 3-17 illustrates an example of joints and base plates for steel supports.

(5) Collar Braces for Steel Supports

Steel supports next to each other are fixed by collar braces. Collar braces shall be properly installed on the newly erected steel supports to prevent collapse until the support is fixed in place by shotcrete. There are two types of the collar braces as shown in Figure 3-18.
Table 3-18 Parameters of Steel Products for Steel Support

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Dimension (mm)</th>
<th>Sectional Area A (cm²)</th>
<th>Density W (kg/m)</th>
<th>Moment of Inertia Ix (cm⁴)</th>
<th>Section Modulus Zx (cm³)</th>
<th>Minimum Radius of Curvature R (cm)</th>
<th>Illustration of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-beam</td>
<td>SS400</td>
<td>H-100×100×6×8</td>
<td>21.59</td>
<td>16.9</td>
<td>378</td>
<td>75.6</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-125×125×6.5×9</td>
<td>30.00</td>
<td>23.6</td>
<td>839</td>
<td>134</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-150×150×7×10</td>
<td>39.65</td>
<td>31.1</td>
<td>1620</td>
<td>216</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-175×175×7.5×11</td>
<td>51.42</td>
<td>40.4</td>
<td>2900</td>
<td>331</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-200×200×8×12</td>
<td>63.53</td>
<td>49.9</td>
<td>4720</td>
<td>472</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-250×250×9×14</td>
<td>91.43</td>
<td>71.8</td>
<td>10700</td>
<td>860</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HT590/</td>
<td>H-154×151×8×12</td>
<td>47.19</td>
<td>37.0</td>
<td>2000</td>
<td>260</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SS540</td>
<td>H-200×201×9×12</td>
<td>65.53</td>
<td>51.4</td>
<td>4782</td>
<td>478</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>U-beam</td>
<td>SM490</td>
<td>MU-21</td>
<td>26.80</td>
<td>21.0</td>
<td>296</td>
<td>56.6</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MU-29</td>
<td>37.00</td>
<td>29.0</td>
<td>581</td>
<td>97.4</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Steel Pipe</td>
<td>STK400</td>
<td>Ø76.3×3.2</td>
<td>7.35</td>
<td>5.8</td>
<td>49.2</td>
<td>12.9</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø89.1×3.2</td>
<td>8.64</td>
<td>6.8</td>
<td>79.8</td>
<td>17.9</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø101.6×5.0</td>
<td>15.17</td>
<td>11.9</td>
<td>117</td>
<td>34.9</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø114.3×4.5</td>
<td>15.52</td>
<td>12.2</td>
<td>234</td>
<td>41.0</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø139.8×6.0</td>
<td>25.22</td>
<td>19.8</td>
<td>566</td>
<td>80.2</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø216.3×8.2</td>
<td>53.61</td>
<td>42.1</td>
<td>2190</td>
<td>269</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ø267.4×9.3</td>
<td>75.41</td>
<td>59.2</td>
<td>6290</td>
<td>470</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Re-bars</td>
<td>SD295</td>
<td>D16×3+D10</td>
<td>6.00</td>
<td>7.4</td>
<td>94.4</td>
<td>26.2</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

* Values of minimum radius of curvature R are by means of the cold processes

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-93)
Figure 3-17  Examples of Joint and Base Plate
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-97)
3.4.8 Lining and Invert

(1) Roles and Functions Required for Lining

Since the roles and functions required for lining are different depending on the purpose of use and conditions of use of the tunnel, it is necessary to design so as to exert the function suitable for them. It also needs to withstand the load acting for a long time and have durable performance with little leakage. The lining, a part of tunnel support, is required to have a mechanical function depending on necessary functions, the provision function for future uncertain factors, and special ground conditions and mechanical conditions as specified below.

1) Functions Related to Service
   - Function to hold section
   - Function to waterproof
   - Function to Refractory
   - Function to Maintenance management
   - Function to interior
   - Function to hold facility

2) Functions for Uncertain Elements
   - Function to retain reserve capacity
   - Function to maintain deformability
   - Function to maintain structural stability

Figure 3-18  Example of Collar Brace
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-98)
3) Function to Mechanical
   - Function to counter the added external force
   - Function to complement the support

(2) Basics of Lining Design
In the design of the lining, it is necessary to examine conditions such as mountain conditions, load conditions and importance of the structure, and to satisfy necessary functions and performance from purpose and conditions of use.
In addition, the lining can be roughly divided into a design that does not add a mechanical function and a design that adds a mechanical function.

1) Design without a Mechanical Function
In the case of NATM of the rock tunnel, it is considered that the mechanical load does not act on the lining because the support is responsible for the load.
The thickness of the lining in this case is basically about 30 to 40 cm.

2) Design with a Mechanical Function
This design is a case where an external force is acting. The external forces are, for example, water pressure, earth pressure and plastic pressure of the expansive ground. In addition, when planning a parallel tunnel or proximity construction, there are cases that water pressure should be taken into consideration (e.g. targeting unconsolidated ground in urban areas). In this case, a numerical analysis is used. Generally, framework structure analysis is carried out, and lamination thickness, rebar strength and concrete strength are determined.

3) Mix and Strength of Lining
The desired strength of lining concrete varies depending upon such conditions as the characteristics of the ground, shape of lining, type of support and load applied to the lining.
The specified concrete strength is often adjusted to about 18 to 30 N/mm² except in special cases.
Table 3-19 lists the specifications of lining concrete for Japanese road tunnels.
(4) Functions of Inverts

Considering that inverts are extremely difficult to repair after the tunnel is put in service, it is necessary to design the inverts to stabilize the surrounding ground by merging into the adjacent tunnel supports, and then to achieve a satisfactory role as a permanent structure carefully considering ground conditions, side conditions, purpose of use and necessary functions and quality.

Inverts are recommended to provide the following functions.

1) For Serviceability
   - Function to hold necessary inner section lining together.
   - Function to provide smooth flow path lining together.

2) For Mechanical Characteristics
   - Function to prevent settlement due to lack of bearing capacity in case of poor ground or displacement of side wall of tunnel induced by plastic earth pressure.
   - Function to enhance structural stability by forming a ring-shaped structure in combination with lining to achieve sufficient load-carrying capacity against earth and water pressure exerted on tunnels in urban areas for a long period.
   - Function to improve durability of tunnel against deformation due to heaving in the ground that is likely to undergo deterioration or swelling, or deterioration due to application of repeated loads before and after construction.
   - Function to improve stability against structural deformation of tunnel by early formation or a ring-like structure which combines with tunnel supports to control convergences of the tunnel during construction similar to temporary invert placed by shotcrete.

3) Shape and Thickness of Invert

   Please refer to chapter 3.2.2 for the thickness and shape of invert.
3.4.9 Waterproofing and Drainage

(1) Waterproofing

For the purpose of preventing leakage into the tunnel, waterproofing should be installed between the shotcrete and the lining. Water leakage to the tunnel will impair its durability; it will lead to an increase in maintenance and repair cost of equipment inside the tunnel. Thus, careful design and construction are required. If the groundwater is high and is not allowed to be lowered, there is an example of making it a no drainage type tunnel because it is not possible to allow leakage to the tunnel. In the rock tunnel waterproofing sheet, the seat system is generally adopted for the following reason.

- It can be installed all around the lining.
- It closely adheres to shotcrete and waterproofing of the whole surface is possible.

The waterproofing sheet needs to have strength and elongation so that it does not break when concrete is put in. The main waterproofing sheet material is Ethylene Vinylacetate Copolymer (EVA), Polyvinyl Chloride (PVC) and Ethylene Copolymer Bitumen (ECB). Also the thickness of the waterproofing sheet is basically 8mm. However, in the case of a no drain type tunnel, the thickness is 1.2 to 1.8 mm. The sheet quality standards in Japan is shown in Table 3-20.

Table 3-20  Quality Standards of Waterproofing Sheet in Japan

<table>
<thead>
<tr>
<th>testing requirement</th>
<th>EVA</th>
<th>PVC</th>
<th>ECB</th>
<th>JIS K 6773</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific gravity</td>
<td>0.95±0.05</td>
<td>1.30±0.05</td>
<td>1.00±0.05</td>
<td>JIS K 6773</td>
</tr>
<tr>
<td>hardness</td>
<td>98 or less</td>
<td>98 or less</td>
<td>98 or less</td>
<td>JIS K 6773</td>
</tr>
<tr>
<td>thickness</td>
<td>The average value of 5 measurement points in the axial direction must be equal to or greater than the specified thickness and minimum thickness is within -5%</td>
<td>JIS K 6773</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>20℃</td>
<td>15.7 or more</td>
<td>15.7 or more</td>
<td>9.8 or more</td>
</tr>
<tr>
<td></td>
<td>-10℃</td>
<td>29.4 or more</td>
<td>19.6 or more</td>
<td>17.7 or more</td>
</tr>
<tr>
<td>elongation</td>
<td>20℃</td>
<td>600 or more</td>
<td>280 or more</td>
<td>500 or more</td>
</tr>
<tr>
<td></td>
<td>-10℃</td>
<td>500 or more</td>
<td>100 or more</td>
<td>350 or more</td>
</tr>
<tr>
<td>tear strength(N/mm²)</td>
<td>49.0 or more</td>
<td>39.2 or more</td>
<td>38.2 or more</td>
<td>JIS K 6301</td>
</tr>
<tr>
<td>flexibility(℃)</td>
<td>-30 or less</td>
<td>-30 or less</td>
<td>-30 or less</td>
<td>JIS K 6773</td>
</tr>
<tr>
<td>chemical resistance</td>
<td>alkali(%)</td>
<td>±1 within</td>
<td>±1 within</td>
<td>±1 within</td>
</tr>
<tr>
<td>mass change</td>
<td></td>
<td></td>
<td></td>
<td>JTA</td>
</tr>
<tr>
<td>Joint strength</td>
<td>(survival ratio%)</td>
<td>30 or more</td>
<td>30 or more</td>
<td>30 or more</td>
</tr>
</tbody>
</table>

(Source: JICA project)

As a general structure of the waterproofing sheet, a composite laminated sheet having a thickness of 0.8 mm and a backside drainage material having a basis weight of 300 g / m² or
more is used.

Figure 3-19  Examples of Waterproofing and Drainage
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-109)

Figure 3-20  Example of Waterproofing Sheet (left) and Installation of Waterproofing Sheet (right)
(Source: Material Manufacturer)

(2) Drainage
The tunnel must be designed with appropriate drainage so that water flowing in the tunnel can be discharged without stagnation. For appropriate drainage in the tunnel, it is necessary to install suitable drainage materials in advance with the proper method and interval so that the water flowing surely drains from the lining wall. In order to let the water on the back of the waterproofing sheet flow down to the drainage, a drain pipe and a water collecting material are installed on end of waterproofing sheet. Then, the collected water is guided to the central drain pipe ditch by a transverse pipe ditch.
3.5 Planning

3.5.1 Excavation Methods

The classification and characteristics of excavation methods are shown in Table 3-21 and Table 3-22. Excavation methods widely used are the full face method, bench cut method and drift advancing method. The counter diaphragm method is also used for projects of large sections and tunneling in urban areas.
<table>
<thead>
<tr>
<th>Excavation Method</th>
<th>Division of Heading</th>
<th>Applicable Ground Conditions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Face Method</td>
<td></td>
<td>- Almost all ground for small section tunnels</td>
<td>- Labor saving by mechanization</td>
<td>- Full tunnel length cannot necessarily be excavated by full face alone. Auxiliary bench cut will be adopted as required. Unsteady stones from the crown may fall down with increased energy, and additional safety measures are required.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Very stable ground for large section tunnels (A=60m²)</td>
<td>- Construction management including safety control is easy because of the single-face excavation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Fairly stable ground for medium section tunnels (A=30m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Unfit for relatively good ground interspersed with bad ground that may require change of the excavation method</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Full Face Method with Auxiliary Bench Cut

- Fairly stable ground, but difficult to apply full face method
- In case that full face method becomes difficult during construction
- Relatively good ground interspersed with bad ground

Bench length 1\(\approx\)2 - 4m

- Labor saving by mechanization and parallel excavation of top heading and bench
- Construction management including safety control is easy because of the single-face excavation.
- Difficult to switch to other excavation methods when the face becomes unstable

Long Bench Cut Method

- Fairly stable ground, but difficult to apply full face method
- Ring cut method is applied when the face is unstable.

Bench length > 5D

- Alternate excavation of top heading and bench reduces equipment and manpower.
- Alternate excavation lengths the construction period.

Short Bench Cut Method

- Ring cut method is applied when the face is unstable.

D < Bench length < 5D

- Adaptable to changes in ground conditions
- Alternate excavation of top heading and bench reduces equipment and manpower.
- Parallel excavation makes it difficult to balance the construction cycle of top heading and bench.
- Alternate excavation lengths the construction period.

Mini Bench Cut Method

- In case convergence needs less control than short bench cut method
- Spacing ground that requires an early closure of excavation cross section
- Ring cut method is applied when the face is unstable.

Bench length < D

- Easy to make early closure by invert
- Alternate excavation of top heading and bench reduces equipment and manpower.
- Selection of construction equipment tends to be limited when they are planned to work on the top heading bed.
- Large deformation may develop if the closure is delayed in bad ground.
- Each bench length is limited and working space is restricted.
- Careful operation of mucking at each bench is required.

Multiple Bench Cut Method

- Fairly good ground for high and large section tunnel
- Bad ground that requires small section of heading to stabilize the face

- Face is easily stabilized.

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-54)
## Table 3-22: Classifications and Characteristics of Excavation Methods (2)

<table>
<thead>
<tr>
<th>Excavation Method</th>
<th>Division of Heading</th>
<th>Applicable Ground Conditions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center Drift Advancing Method</strong></td>
<td><img src="center-drift.png" alt="Diagram" /></td>
<td>- Soil ground with shallow overburden where ground surface settlement is required to be kept at a minimum. - Relatively bad ground for large section tunnel.</td>
<td>- Face is stabilized by dividing into small sections. - Ground surface settlement can be reduced. - Divided sections of heading are larger than those in side-drift method, and larger equipment can be used.</td>
<td>- Displacement or settlement by removal of diaphragm should be examined. - Removal of diaphragm is added to the construction process. - The adoption of a special auxiliary method in the tunnel is difficult.</td>
</tr>
<tr>
<td><strong>Side Wall Drift Advancing Method</strong></td>
<td><img src="side-drift.png" alt="Diagram" /></td>
<td>- Ground where bearing capacity is insufficient. - Soft rock ground or soil ground with shallow overburden where unexpected ground pressure or landslide is anticipated.</td>
<td>- Relatively massive concrete wall for side drift improves the bearing capacity and withstands resistance against unexpected ground pressure. - Small equipment has to be used for drift excavation. - The upper ground may be lowered by drift excavation.</td>
<td></td>
</tr>
<tr>
<td><strong>without Side Wall Concrete</strong></td>
<td><img src="side-drift.png" alt="Diagram" /></td>
<td>- Ground where bearing capacity is insufficient to apply bunch cut method. - Soil ground with shallow overburden where ground surface settlement is required to be kept at a minimum.</td>
<td>- Ground surface settlement can be reduced. - Temporary diaphragm can be more easily removed than those in center diaphragm method. - Small equipment has to be used for drift excavation.</td>
<td></td>
</tr>
<tr>
<td><strong>Top Drift Advancing Method</strong></td>
<td><img src="top-drift.png" alt="Diagram" /></td>
<td>- Ground that requires the confirmation of geology, drainage effect and the reduction in preceding displacement and supporting pressure. - TBM may be adapted to advance drift.</td>
<td>- The confirmation of geology, drainage effect and the reduction in preceding displacement and supporting pressure can be achieved by advancing drift. - Center cut is unnecessary in drill and blast method. Blasting vibration and noise can be therefore reduced. - Face stability can be improved when enlarged.</td>
<td>- Drift excavation by TRM may take time as the ground is fairly stable. - Small equipment has to be used for drift excavation.</td>
</tr>
<tr>
<td><strong>Other Drill Advancing Methods</strong></td>
<td><img src="other-drift.png" alt="Diagram" /></td>
<td>- Ground that requires the confirmation of geology, drainage effect and the reduction in preceding displacement and supporting pressure.</td>
<td>- The confirmation of geology, drainage effect and the reduction in preceding displacement and supporting pressure can be achieved by advancing drill. - Center cut is unnecessary in drill and blast method. Blasting vibration and noise can be therefore reduced. - Face stability can be improved when enlarged.</td>
<td>- Small equipment has to be used for drift excavation.</td>
</tr>
<tr>
<td><strong>Bottom Drift Advancing Method</strong></td>
<td><img src="bottom-drift.png" alt="Diagram" /></td>
<td>- Geology can be confirmed by advancing drill. - Additional face is produced from drift, and construction period can be shortened.</td>
<td>- Difficult to balance the construction cycle of each face. - Various types of equipment are required.</td>
<td></td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-55-56)
3.5.2 Excavation Driving Method

Excavation driving methods include drill and blast, mechanical excavation, and combinations of these methods. As a general rule, the main concern in the selection of the excavation driving method is the ground condition. The drill and blast method is mainly applied to hard or medium hard rock ground. The mechanical method is usually applied to medium hard rock or soil ground. Excavation equipment should be properly selected in consideration of tunnel length and ground properties. TBM can be also used for a relatively long tunnel in hard or medium rock ground. When applying the TBM method, excavation efficiency and countermeasures against problems should be studied exhaustively in advance. In Japan, the excavation driving method is decided by the following flow.

Figure 3-23 Full Face Method with Auxiliary Bench Cut (left) and Short Bench Cut (right)

Figure 3-24 Side Drift Advancing Method (left) and Top Drift Advancing Method (right)
(Source: JICA project)
Selection of Excavation driving Method

- **Do you need environmental measures for noise and vibration?**
  - **YES**
  - **NO**

- **Whether section D type occupies about 90% of total length and uniaxial compressive strength of bedrock less than 49 N/mm²?**
  - **YES**
  - **NO**

- **Uniaxial compressive strength of bedrock is more than 49 N/mm² and D Type occupies 90% or less of total length**
  - **Blasting**
  - **Mechanical excavation: Boom Header or TBM**
  - **another excavation method**

**Figure 3-25 Flow of Selection Excavation Driving Method**
(Source: JICA project)

**Figure 3-26 Drilling and Blasting**
(top-left), Mechanical Excavation by Boom Header (top-right) and Mechanical Excavation by TBM (bottom-left)
(Source: JICA project)
3.5.3 Mucking

There are three transport methods.
- Road hauling
- Rail hauling
- Belt conveyer

The muck transport methods in the tunnel are shown in Table 3-23. Road hauling uses load haul dump truck and large dump truck (20-40T). Rail hauling uses shuttle cars. Other types of hauling are container method, conveyer method, and capsule method.

TBM for small cross section uses the fluid hauling method.

When selecting the mucking method, their size and number shall be determined appropriately for the tunnel sectional area and mucking capacity.

The capacity of the temporary muck yard should be suitably planned considering the quantity of muck during construction, hauling system, road traffic situation and muck receiving structure so that problems may not arise during tunnel drilling.
### Table 3-23  Comparison of the Typical Mucking Methods in Tunnels

<table>
<thead>
<tr>
<th>System</th>
<th>Overview</th>
<th>Ease of work</th>
<th>Environment in the tunnel</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road hauling</td>
<td>Dump truck</td>
<td>- Muck loading is interrupted when the truck is made to wait.</td>
<td>- Since internal combustion engines are used, sufficient ventilation shall be provided in the tunnel.</td>
<td>- A turntable may be required to change the direction of dump trucks. (dump truck, large-dump truck, and load hole dump truck)</td>
</tr>
<tr>
<td></td>
<td>Turntable</td>
<td>- Complicated truck traffic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road hauling</td>
<td>Container type</td>
<td>Two or more containers are temporarily placed inside the tunnel, aimed at early opening of the face.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road hauling</td>
<td>Muck car</td>
<td>Muck is loaded on mucking carriages with a Shaff loader, and is carried outside the tunnel.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single track</td>
<td>- Muck loading is interrupted when the truck is made to wait.</td>
<td>- Use of battery powered engine keeps clean environment inside the tunnel.</td>
<td>- Track equipment</td>
</tr>
<tr>
<td></td>
<td>Double track</td>
<td>- When trains with multiple cars are used, their operation shall be managed properly.</td>
<td></td>
<td>- With a single track, a shunting section is needed.</td>
</tr>
<tr>
<td>Road hauling</td>
<td>Shuttle car</td>
<td>A shuttle car is used instead of mucking truck. Muck is loaded at the end of the shuttle car, and transported backward by the chain conveyor on the vehicle floor.</td>
<td>- Same as above</td>
<td>- Same as above</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belt conveyor</td>
<td></td>
<td>- Along with advance of the face, additional conveyor belts, conveyor frame and booster drive are necessary.</td>
<td>- Since no internal combustion engine is used, the environment inside the tunnel can be kept clean.</td>
<td>- Conveyor belt</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Conveyor frame</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Extension equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- For drill and blast, a crusher is necessary.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-149)
3.5.4 Selection of Spray Shotcrete

There are two types of spray shotcrete: dry-process shotcrete and wet-process shotcrete. Although wet-process shotcrete is generally adopted, the method is chosen depending on scale of construction, volume of shotcrete and other conditions. Systematic diagram of dry-process spray shotcrete and wet-process spray shotcrete are shown in Figure 3-28. Characteristics of spray shotcrete methods are shown in Table 3-24.

![Diagram of Shotcreting Method](Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-154)

![Shotcreting Machine (left) and Shotcreting (wet-process, right)](Source: JICA project)
Table 3-24 Characteristics of Shotcreting Methods

<table>
<thead>
<tr>
<th>Items</th>
<th>Dry process</th>
<th>Wet process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics related to mix design management</td>
<td>Depending on the condition (dry or wet) of the target surface of shotcreting, the water-cement ratio can be altered at the nozzle section. Since the water-cement ratio is dependent upon the skill of the nozzlemen, the variance in the mix formula may vary greatly in some cases. The water flow rate can be controlled to limit fluctuations of the water-cement ratio.</td>
<td>With base concrete produced at a plant, management equivalent to that for conventional concrete is possible.</td>
</tr>
<tr>
<td>Strength characteristics (Initial strength)</td>
<td>Initial strength develops more quickly than in the wet process due to the fact that the water-cement ratio generally tends to be lower than in the wet process.</td>
<td>Initial strength develops more slowly than in the dry process due to the fact that the water-cement ratio generally tends to be greater than in the dry process for the purpose of securing pumpability.</td>
</tr>
<tr>
<td>Workmanship</td>
<td>Because the development of the strength immediately after shotcreting is great, the surface with shotcrete applied relatively easily attains smooth surface.</td>
<td>Probably because the development of the strength immediately after shotcreting is relatively slow, the surface with shotcrete applied tends to be rough, depending on the types of aggregates that stick to the surface later.</td>
</tr>
<tr>
<td>Pumping distance</td>
<td>Horizontal: 150<del>300m (max:1,000m) Vertical: 100</del>150m</td>
<td>Horizontal: 100 m Vertical: 30-50m</td>
</tr>
<tr>
<td>Construction capacity</td>
<td>Max. 12m³/h</td>
<td>Max. 20 m³/h</td>
</tr>
<tr>
<td>Dust</td>
<td>It is possible to reduce dust generation to some extent by defining the pumping method, the type of set accelerating agent, gunning method, mix of the dry-mixed concrete, etc. appropriately. Typically, this process involves a higher level of dust generation compared to the wet process application.</td>
<td>It is possible to reduce dust generation to some extent by appropriately defining the pumping method, the type of set accelerating agent, gunning method, mix of the base concrete, etc. Typically, this process involves a lower level of dust generation compared to the dry process application.</td>
</tr>
<tr>
<td>Rebound</td>
<td>It is possible to reduce rebound by defining the pumping method, the type of set accelerating agent, gunning method, mix of the dry-mixed concrete, etc. appropriately.</td>
<td>It is possible to reduce rebound by defining the pumping method, the type of set accelerating agent, gunning method, mix of the base concrete, etc. appropriately.</td>
</tr>
<tr>
<td>Measures against water ingress</td>
<td>Possible to cope with since adjustment of mix design is easy.</td>
<td>Difficult to cope with since adjustment of mix design is not easy.</td>
</tr>
<tr>
<td>Time from mixing to gunning</td>
<td>Depending on the surface moisture volume of the aggregates, greater flexibility compared to the wet-process allocation.</td>
<td>Within 1.5 hours (at a temperature exceeding 25°C) Within 2.0 hours (at a temperature of 25°C or lower)</td>
</tr>
<tr>
<td>Production equipment, Shotcreting equipment</td>
<td>While there is some large-scale shotcreting equipment, simple and highly mobile equipment can be used. The production equipment does not need to incorporate turbid water treatment equipment.</td>
<td>The shotcreting equipment tends to be large in scale, often requiring a plant on the site. The production equipment needs to incorporate turbid water treatment equipment.</td>
</tr>
<tr>
<td>Cleaning</td>
<td>No more than an air-cleaning level is required for the machinery, batcher plant and hose.</td>
<td>Complete water washing is required for the shotcreting machine, production equipment, and hose.</td>
</tr>
</tbody>
</table>

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-154)
3.5.5 Lining Forms

Moving forms are used for lining concrete casting. The moving forms consist of a set panels (metal form) or skin plates and framed structure, gantry and accessories. The following two types are commonly used: moving forms and assembled forms.

The moving forms are produced that can move as a single unit on a moving platform by incorporating a framed structure with steel plates or skin plates. The assembled form is designed so that the framed structure and steel panels are assembled and dismantled each time when the concrete is being poured. The assembled forms are basically used for enlargement areas. However, moving forms are usually used for lining. The length of moving form is a span of one section of concrete. One section of moving form is determined considering the work schedule, concrete supply capacity and curve radius of alignment. A basically length of the form is 9 to 12m., because longer length of the one section of the form can cause cracks due to thermal drying shrinkage.

Figure 3-30 Example of Moving Form (1)
(Source: JICA project)

Figure 3-31 Example of Moving Form (2)
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-160)
Forms should not be released until the concrete is strong enough that it can be worthy of holding its own weight. The time when a form may be removed varies depending on the type of concrete, the size of the tunnel, the shape of the tunnel, the lining width and the construction season. Basically the forms are removed 12 to 20 hours after the placement of concrete. For a round arch tunnel, the strength of the concrete at the time of form removal is often controlled with the reference value of concrete compressive strength of about 2 to 3 N/mm².

3.5.6 Construction of Portals

During the construction of portals, the post-excavation slope gradient should preferably be minimized to prevent ground failure while excavating in order to stabilize the portal slope and to facilitate construction. To that end, the slope should be reinforced by applying shotcrete on the slope or installing rock bolts to proactively stabilize the ground at the portal.

The typical methods of portals construction are shown in Figure 3-33.

Figure 3-33  Typical Sequence of Portal Construction
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-172)
4 Auxiliary Methods

4.1 Concept of Auxiliary Methods

In the tunnel construction period, an additional construction method is necessary in cases that it is impossible to keep excavation stability, to excavate safely, to minimize the influence on surrounding environment, and to satisfy management standard value. This method is called an auxiliary method. The auxiliary construction method can be roughly divided into a construction method that can be constructed with basic machine equipment and a construction method using a special machine. Mountain tunnels are premised on a stable face. Therefore, the most dangerous area is the face immediately after drilling and the unsupported section of drilling progress. From this, the auxiliary method is carried out to maintain the stability of the face and unsupported section. When considering the auxiliary method, it is necessary to pay attention to the following points.

- Topography and geological conditions should be thoroughly considered.
- Distribution of groundwater should be understood.
- The plastic region occurring ahead of the face can’t be controlled by the support after excavation
- The expansion of the plastic region generated ahead of the face affects looseness (speed, area) after excavation.

Figure 4-1 shows the flow of surveys, design and tunnel construction, which summarized from the viewpoint of the auxiliary method.
4.2 Application of Auxiliary Methods

Auxiliary methods are classified into categories according to their objectives: face stabilization, groundwater control, reduction of face settlement and reduction of influence on neighboring structures. Auxiliary methods should be selected that are superior in terms of safety, effects and cost performance evaluating the condition ahead of face and face itself. Several kinds of auxiliary methods are used at the same time according to circumstances.
Efficient and cost effective auxiliary methods should be selected by thoroughly evaluating not only tunnel construction methods and ground conditions, but also environmental conditions. Table 4-1 lists typical methods among various auxiliary methods currently used in Japan.

Table 4-1  Classification of Auxiliary Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose</th>
<th>Ground to which method can be applied</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Construction safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Face stabilization</td>
</tr>
<tr>
<td>Forepoling (filling, grouting)</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Steel pipe forepoling (grouting)</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Pipe roof</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Horizontal jet grouting (injection and mixing)</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Slit concrete method</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Face shotcrete</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Face bolt</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Long face bolt</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Footing reinforcement bolt</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Footing reinforcement pile</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Temporary invert</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Drainage boring</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Well point</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Deep well</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Drainage drift</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Grouting</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cut-off wall</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Ground reinforcement</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Note: ○: relatively common method,

*1: measures that are difficult to implement with conventional tunnel construction machinery and facilities control.

*2: Method that requires modification of tunnel construction machines and materials depending upon the specific technique selected.

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-177)
4.2.1 Stabilization Methods of Crown

A NATM tunnel is premised on the stability of the cutting face and the crown of the tunnel until supports have been set up.

If the ground is weak and the cutting face does not become self-supporting, an auxiliary method to hold the face will be needed.

Ground stabilization for the face can be classified into three categories according to the site at which they are applied.

- Stabilization of the crown
- Stabilization of the face
- Stabilization of the footing

It is important to plan countermeasures against possible instability in advance, to continually evaluate the face stability by observation and other methods, and to execute the plan before it becomes too late.

(1) Filling Type Forepoling

Filling type forepoling use the bolts, steel bars or pipes, which are a length of less than 5m. They are driven into the ground around the top heading arch, as shown in Figure 4-2. The aim of the method is to increase the shear strength of the ground at the crown and to prevent the loosing of ground ahead of the face. This method is generally used for preventing collapse or falling of the crown and is often implemented at an early stage of stabilization.

![Figure 4-2 Example of filling type forpoling](image-url)

(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-179)
(2) Grouting Type Forepoling
Grouting type forepoling uses the hollow bolts, or pipes, which are length of less than 5m. They are driven diagonally into the ground ahead of the face, with simultaneous injection (under pressure) of quick-setting cement paste or a chemical grout, in order to enhance the stability of the crown ahead of the face, as shown in Figure 4-3.

Figure 4-3  Example of Grouting Type Forepoling
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-180)

(3) Pipe Forepiling
Pipe forepiling is an auxiliary method for reinforcing unstable ground, such as talus, fault fracture zone or unconsolidated ground, where the ground arch is not expected. An additional benefit of the method is a reduction in prior displacement. Usually steel pipe longer than 5m in length is used. This method is mainly used for stabilization of the crown. However, it may require a change in the excavation cross section or kind of machinery used in the application. Therefore it is necessary to check the time schedule before adopting this method. Pipes are inserted into the ground along the upper perimeter of the planned excavation cross section prior to tunnel excavation, but the exact arrangement of pipes varies depending on the ground conditions and the position of nearby structures.
There are two methods; one with specialized machines and the other with a drill jumbo. The method using a drill jumbo is usual. Filling type forepiling, which can also be used for improving ground stabilization, achieves a tight contact between steel pipes and ground by filling the space between the steel pipes and the ground with a grout, such as cement paste. Another example is the grouting type forepiling method that forms composite reinforcements consisting of steel pipes and grout material, where the ground is reinforced by injecting cement paste or chemical grout into the ground around the steel pipes.
4.2.2 Stabilization Methods of the Face

There are ground stabilization methods for the cutting face such as ring cutting, shotcreting, face bolting and grouting. Face stability is affected by both the scale and shape of the cutting face. In order to improve the face stability, it is important to spray concrete as early as possible by excavating the face part by part.

(1) Face Shotcrete

Face shotcrete is sprayed onto the face at the thickness of 3 to 10cm as soon as it is excavated in order to increase the stand-up time of the face as shown in Figure 4-5.
(2) Face Bolt and Long Face Bolt
There are two types of face bolts. One is slightly shorter than 5m length; the other is longer than 5m. The purpose of the face bolt is to stabilize the cutting face and reduce the ground surface settlement by supporting a part or the whole of the face with rock bolts. Face bolting is more effective when used in conjunction with face shotcrete. The length of the face bolts should ideally maintain an effective residual length when they are cut by tunnel excavation. Grouting face bolts may be used for an increased reinforcement. Glass fiber reinforced plastic bolts are often used because they are easy to cut.

![Face Bolt and Long Face Bolt](image)

Figure 4-6  Example of Face Bolts
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-181)

(3) Grouting
Grouting is a method for stabilization of the face in which cement materials (such as cement paste) or chemical materials (such as water-glass grout) are injected into the ground for soil improvement. One purpose of grouting is to reduce water inflow into the tunnel lowering the permeability of the soil. Another purpose is to stabilize highly fractured ground that is likely to collapse.
4.2.3 Stabilization Methods of the Footing

Stabilization methods for the footing help protect against damage by foot settlement caused by lack of the bearing capacity of the ground. Methods include shotcreting (for top heading temporary inverted arch), downward bolting (in which rock bolts or steel pipes are used at the footing supports) or jet grouting. These methods increase the bearing capacity of the ground.

(1) Top Heading Temporary Inverted Arch

Generally, a top heading temporary inverted arch temporarily closes the top heading bed by shotcreting. This is a very efficient method. This method has the advantage of being able to base construction on face conditions and results of monitoring. However, since the temporary top heading invert must be removed, the efficiency of bench excavation will be reduced.
(2) Foot Reinforcement Bolt and Pipe

Foot reinforcement bolt and pipe (installation of downward-facing rock bolts at the footing of supports or small-diameter steel pipes, and jet grouting) have the purpose of reducing the stresses in the contact ground of the heading support and preventing the collapse of the ground during bench excavation. If the strength of the ground around the footing is lower, the injecting bolts with cement paste grouting or chemical grouting can increase the strength of the ground.

Figure 4-9  Example of Reinforcement Foot Pile and Side Pile
(Source: Standard Specifications For Tunneling-2006: Mountain Tunnels, 2007, Japan Society of Civil Engineers, P-183)
4.2.4 Auxiliary Methods of Controlling Water Inflow

If the amount of water inflow is large during tunnel excavation, it will be a big problem. There is possibilities to occur lack of face stability, collapse of the face, insufficient adherence of shotcrete and rock bolts, and decreased tunneling work efficiency.

Countermeasures to control water inflow can be classified into two categories:

- Drainage methods
- Water sealing methods

(1) Drainage Methods

Drainage methods are more widely used than water sealing methods. However, prevention on the groundwater level lowering may be inadequate in some cases (due to ground surface conditions in the surrounding environments, and/or the abundance of groundwater). Therefore, drainage methods should be selected by considering the above subjects.

1) Drainage Boring

Drainage boring is a widely used method. This method removes groundwater through the boreholes drilled by a boring machine or drill jumbo in order to lower water pressure and the groundwater level. However, drainage boring on the unconsolidated ground needs to pay attention for the outflow of the sediment.

2) Drainage Adit

Drainage adit, approach of providing a pilot adit of small diameter, is often used in conjunction with drainage boring for sites with a large amount of groundwater. A lot of adit may be required at an aquifer with high water pressure.
3) Well Point Drainage

Well point drainage is a method used for removing groundwater under negative pressure, in which groundwater collecting pipes called “well points” are inserted into the ground. The well point is a water pipe with a diameter of 2 to 2.5 inches and a length of 0.7 to 1 m and a water collecting device called a well point attached to the tip of a special pipe (about 1.5 inch diameter, about 7 m in length) by a water jet. It is a construction method which lowers the groundwater level by driving into the ground, vacuuming suction and draining it.
5 Outline of Tunnel Equipment Design

5.1 Outline
Fixtures including ventilation, lighting and emergency devices are installed in road tunnels for safety in traffic by considering tunnel length, traffic volume and other conditions. Ventilation equipment is one of the most basic devices for securing the safety of tunnel users and smooth traffic.

5.2 Ventilation Equipment
5.2.1 General Ventilation Plan
Ventilation is required for preventing air pollution inside a tunnel due to the exhaust gas from automobiles running inside the tunnel. If the tunnel length is short, natural ventilation suffices in some cases, but if the tunnel length is long and traffic volume is large, ventilation equipment is necessary.

5.2.2 Discussion on the Necessity of Ventilation Equipment
Necessity of ventilation equipment for two way tunnels can be judged according to the following empirical equation in Japan:

\[ L \cdot N = 600 \]

Where, \( L \): tunnel length [km]
\( N \): traffic volume per hour [vehicles/h]

\[ L \cdot N < 600 \quad \text{Ventilation is unnecessary} \]
\[ L \cdot N > 600 \quad \text{Ventilation is necessary} \]

This equation is based on Japanese emission regulations. However, there is no emission regulation in Sri Lanka. Therefore, it is recommended to revise the equation considering Sri Lankan situation. Furthermore, detailed examination is necessary in the detail design stage because this formula is an outline examination method.
5.3 Lighting Equipment

5.3.1 Purpose of Road Lighting
Road lighting is aimed at securing good visibility to see road and traffic conditions accurately in places where brightness changes abruptly, such as tunnels, and achieving safe and smooth road traffic. In the case of tunnels, road lighting equipment is installed according to tunnel length traffic volume and other conditions.

5.3.2 Compositions of Tunnel Lighting
The compositions of tunnel lighting are as follows:

a. Basic lighting (tunnel body lighting)
b. Inlet lighting
c. Outlet lighting
d. Lighting for power outage
e. Lighting for connection roads
One way Tunnel

Figure 5-2  Example of Lighting System (one way tunnel)
(Source: JICA project)

Legend

- Basic lighting
- Inlet lighting
- Outlet lighting
- Lighting for connection roads

Two way Tunnel

Figure 5-3  Example of Lighting System (two way tunnel)
(Source: JICA project)
5.3.3 LED Lighting
Light emitting diode (LED) lighting is expanding its use in various applications along with improvements in technology and cost reduction of lamps, which aims at the reduction of lighting cost and power consumption.
In Japan, LED road / tunnel lighting design guidelines were created in 2015, and all new tunnels are installed with LED lighting based on this guideline. From economic efficiency and durability, it is desirable to design tunnel lighting based on LED lighting.

![Figure 5-4 Example of LED](Source: Manufacturer catalog)

5.4 Emergency Equipment
Since a tunnel is a closed space, it is necessary to sufficiently consider anti-disaster measures for fire, tunnel collapse and other disasters. Anti-disaster measures for tunnels are composed of safety of tunnel users, the observance of legal regulations, and emergency equipment for minimizing the damage due to accidents. In Japan, the tunnel grade is defined by the traffic volume and tunnel length to determine the necessity of emergency equipment. The criteria and list of emergency equipment are shown in Figure 5-5 and Table 5-1.
Main purposes of the emergency equipment are emergency notification, fire extinguishing and evacuation guidance. However, the criteria shown in Figure 5-5 are for outline design based on Japanese experiences. Therefore, it is necessary to revise the criteria considering the traffic condition in Sri Lanka.
The other issue is operation and maintenance (O/M) of the emergency equipment. It is necessary to fix O/M system in RDA for emergency equipment because the emergency equipment requires O/M organizations (e.g. 24/7 call center and/or maintenance division) and budgets. Hence, the O/M organization structures and the budgets must be ensured to decide the detail specification and quantity of the emergency equipment.
Figure 5-5  Tunnel Classification
(Source: Road Tunnel Emergency Facility Installation Criteria Commentary, 2001, Japan road association P-9)

Table 5-1  Emergency Equipment by Tunnel Classification

<table>
<thead>
<tr>
<th>Emergency equipment</th>
<th>Tunnel grade</th>
<th>AA</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notifying and alerting devices</td>
<td>Emergency telephones</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Push button call units</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Fire detectors</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emergency alarms</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Fire extinguishing equipment</td>
<td>Fire extinguishers</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrants</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evacuation guidance equipment</td>
<td>Guidance display panels</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Smoke vents or evacuation passages</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other devices</td>
<td>Water plugs</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wireless communication supporting equipment</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radio repeating devices or public-address systems</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water spray apparatus</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monitors</td>
<td>○</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

○: Installation required
△: Decide after consultation with other agencies

(Road Tunnel Emergency Facility Installation Criteria · Commentary, 2001, Japan road association P-14)
6 Outline of Alignment Standard in Japan

Road design is defined by a combination of horizontal alignment and vertical alignment, and is closely related to design speed. Regulation of horizontal alignment is composed of curvature radius, superelevation of curvature and transition curve. The definition of vertical alignment consists of longitudinal slope and longitudinal curve. The alignment standards shown in following sections are based on Japanese traffic condition. Therefore, those standards should be revised considering actual traffic condition in Sri Lanka.

6.1 Horizontal Alignment

6.1.1 Curve of Road

Curve of road consists of a curve section and transition section. It is desirable to use a clothoid curve close to the actual transition curve.

6.1.2 Radius of the Curvature

The radius of curvature of the center line shall be not less than the value of the Table 6-1. When it is unavoidable to set less radius of curvature due to the topographic situation and other limitations, it is possible to reduce the number in the right column.

<table>
<thead>
<tr>
<th>Design Speed (km/h)</th>
<th>Curve radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>not less than the following figure</td>
<td>minimum</td>
</tr>
<tr>
<td>120</td>
<td>710</td>
</tr>
<tr>
<td>100</td>
<td>460</td>
</tr>
<tr>
<td>80</td>
<td>280</td>
</tr>
<tr>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>

(Source: Japanese road structure order)

6.1.3 Superelevation (slope) of Curvature

The curvilinear portion is provided with a single gradient to alleviate the force that the automobile receives in the lateral direction. The superelevation is determined by the design speed and the curve radius.
6.1.4 Desired Curve Radius

A value that guarantees the comfort of running of vehicle is shown in Table 6-2.

6.1.5 Transition Curve

It is required to consider a transition curve to prevent sudden steering wheel operation caused by sudden change of linearity and shock to occupants. The transition curve length shall be not less than the value listed in Figure 6-2 according to the design speed.
6.2 Vertical Section Alignment

6.2.1 Longitudinal Slope

In order to avoid a decline in the traffic capacity of the road caused by a vehicle with a remarkable drop in speed and a decrease in traffic safety, a longitudinal slope is set according to the design speed. The longitudinal slope shall be less than or equal to the value listed in the Table 6-3 according to the design speed.

Table 6-3 Longitudinal Slope

<table>
<thead>
<tr>
<th>Design Speed (km/h)</th>
<th>Longitudinal slope(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>9</td>
</tr>
</tbody>
</table>

(Source: Japanese road structure order)

6.2.2 Radius of Longitudinal Curves

A longitudinal curve is set at a position where the longitudinal slope changes. The radius of longitudinal curves shall be not less than the following value (Figure 6-3) according to the design speed.

Figure 6-3 Radius of Longitudinal Curves

(Source: Japanese road structure order)
6.3 Visual Range

The visual range is the distance from the observation point with height of 1.2 m on the center of the lane to an object, which can be seen, with height of 10 cm on the center of the same lane.

![Visual Range Diagram]

Figure 6-4 Visual Range
(Source: Japanese road structure order)

- Braking stopping distance

Speed and braking distance are expressed by the following equation.

\[
D = \frac{V}{3.6}T + \frac{V^2}{2gf(3.6)^2}
\]

where,

- \(D\): Braking stopping distance
- \(V\): Speed (km/h)
- \(F\): Friction coefficient of road surface and tire against longitudinal slip
- \(T\): Judgement time and reaction time

According to American Association of State Highway and Transportation Officials (AASHTO), the judgment time and the reaction time is estimated as 1 second and 1.5 second, respectively. Thus, 2.5 s for \(T\) and 9.8 for \(g\) are substituted to the above equation. Then, the following equation is obtained.

\[
D = 0.694V + \frac{0.00394V^2}{f}
\]

Considering the wet road surface, the braking stopping distance (which is corresponding to the visual range) is calculated as the traveling speed from 85% to 90% of the design speed.
<table>
<thead>
<tr>
<th>Design speed (km/h)</th>
<th>Traveling speed (km/h)</th>
<th>$f$</th>
<th>$0.694 \cdot V$</th>
<th>$0.00394 \cdot \frac{V^2}{f}$</th>
<th>$D$ (m)</th>
<th>Criteria (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>102</td>
<td>0.29</td>
<td>70.7</td>
<td>141.3</td>
<td>212.0</td>
<td>210</td>
</tr>
<tr>
<td>100</td>
<td>85</td>
<td>0.30</td>
<td>58.9</td>
<td>94.8</td>
<td>153.7</td>
<td>160</td>
</tr>
<tr>
<td>80</td>
<td>68</td>
<td>0.31</td>
<td>47.1</td>
<td>58.7</td>
<td>105.8</td>
<td>110</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>0.33</td>
<td>37.4</td>
<td>34.8</td>
<td>72.2</td>
<td>75</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>0.35</td>
<td>31.2</td>
<td>22.8</td>
<td>54.0</td>
<td>55</td>
</tr>
<tr>
<td>40</td>
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<td>0.38</td>
<td>24.9</td>
<td>13.4</td>
<td>38.3</td>
<td>40</td>
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<tr>
<td>30</td>
<td>30</td>
<td>0.44</td>
<td>20.8</td>
<td>8.1</td>
<td>28.9</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>0.44</td>
<td>13.9</td>
<td>3.6</td>
<td>17.5</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 6-4  Braking Stopping Distance
(Source: Japanese road structure order)

Braking stopping distance