Design and construction of mountain tunnels in Japan

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Received 10 September 2002; received in revised form 29 January 2003; accepted 4 February 2003

Abstract

This paper presents the state of technologies of the mountain tunneling method in Japan. In addition to the review of the design and construction technologies, the paper focuses on the development of technologies for tunnels with large cross-sections, urban tunnels in non-cemented soil ground, and applications of TBMs, which are technically evolving nowadays.

Keywords: Mountain tunneling; Urban tunnel; TBM

1. Present state of design and construction technologies

1.1. Introduction

In Japan, the mountain tunneling method has become popular since the end of the 19th century. Many tunnels, including those under difficult conditions such as the Seikan Tunnel, have been successfully constructed with advanced technologies.

Approximately 20 years ago, the Japanese mountain tunneling method was changed when it adopted the use of supports which combine shotcrete and rock bolts, or in some cases, steel supports. Since then, design and construction technologies have made more progress. Attempts have been made to create technical development for high-speed construction, using advanced mechanization, and challenges to handle technically difficult tunneling construction works, such as tunnels with large cross-sections, urban tunnels in non-cemented soil grounds, have been met. These efforts have succeeded in advancing the design and construction technologies of mountain tunnels.

1.2. Initial design and modification of the design

In general, a ‘standard cross-section’, specified by an administrator, is adopted in the initial design stage.

The ground can be classified into several general types, and a preliminary design should be made for each ground type.

The initial design methods are as follows.

a. Application of 'standard designs'.

In Japan, administrators of railways, roadways, etc. maintain a list of ground classifications and corresponding standard designs based on past experiences. These standard designs are employed for the construction of tunnels under normal conditions.

b. Application of designs under similar conditions.

c. Application of analytical methods.

For tunnels with special cross-sections or special ground conditions, numerical analyses are employed. The most general type of numerical analysis is the finite element method (FEM).

1.3. Observations, measurements and modified designs

Designs are modified during the construction stage by making judgments and evaluations from the viewpoint of whether or not the ground conditions are the same as those anticipated during the initial design stage. If modifications are required, the following problems must be solved, namely: (1) how to change the amount of support and/or the installation time; (2) whether or not the stability of the cutting face can be maintained if construction is continued; and (3) if unstable, what rational measures should be taken.
1.3.1. Evaluation of the ground

It is very important to observe the cutting face and to evaluate the ground conditions. However, there are many factors which have to be systematically taken into account. An attempt is made to compute the percentage that each factor contributes by analyzing past records and by expressing the ground conditions in terms of evaluation points.

1.3.2. Probing exploration

In order to speed up the construction time, it is particularly important to properly evaluate the ground conditions. To meet this goal, an investigation should be conducted to evaluate the ground conditions ahead of the cutting face. In addition to pilot boring, an estimation method which involves drilling energy or elastic waves is adopted.

1.3.3. Use of measurements

In order to evaluate the present state of the ground conditions with the measurements, the following maintenance targets are often set up.

- Evaluation of the stability of the ground; Sakurai (1982) and Sakurai et al. (in press) proposed a method for estimating an allowable value of displacement from relationship between the limit strain and the uniaxial compressive strength.
- Maintaining limits for the soundness of the supports.
- Limits not to influence the surrounding structures.

1.4. Support designs

1.4.1. Shotcrete

A strength of 18 MPa (a curing period of 28 days), as high as lining concrete, is used as the standard design strength. In cases where the thickness needs to be increased, attempts are sometimes made to either apply reinforcements using steel fiber or to increase the standard design strength, just like the tunnels for the New Tomei and the New Meishin Expressways or tunnels with thick overburdens (Miura et al., in press).

Shotcrete is sometimes reinforced by the insertion of wire nets. Steel fiber reinforced concrete is used when complicated stress or large deformation develops.

A new support is under development along with new construction methods, namely, shot mortar, extruded concrete lining (ECL), prelining, and so on.

1.4.2. Rock bolts

Rock bolts are used as primary support materials just like shotcrete. The main anchorage method for rock bolts is a full-faced anchorage. For cases in which a rock bolt hole cannot stand alone, a self-boring type of rock bolt may be employed. When rock bolts are anchored to the ground, the friction is increasing. The bolts are not only effective immediately after installation, but also work even when water inflow is encountered.

1.4.3. Steel supports

Steel supports are considered to have positive effects such as early stabilization of the crown face, reinforcement of shotcrete, supporting points of fore-piling, etc., and they are generally used in Japan when ground conditions are poor.

1.5. Design of the lining

At general sites and under normal ground conditions, the purpose of a lining is to increase the safety of the supports. Thus, no particular consideration is given to the mechanical functions. It is conventional practice to apply a standard design.

Mechanical consideration does need to be given to the design of the lining in some cases; for example, the earth pressure or the water pressure acts after the completion of the tunnel. Some engineers refer to past similar cases, and then conduct a structure analysis or a finite element analysis.

1.6. Auxiliary methods

In mountain tunneling, the auxiliary methods can be used in order to stabilize an unstable cutting face, to control the preceding displacement ahead of the cutting face, to improve the ground conditions so as to obtain the full effect of the supports, and so on.

1.6.1. Stabilizing the crown

The crown is stabilized in order to prevent its collapse before the shotcrete has been applied and has hardened. Fore-piling, in which rock bolts are driven into the ground around the excavated face, is easy to conduct without changing the arrangement of the construction machines used at conventional construction sites.

Pipe roof protection, horizontal jet grouting (Fig. 1), long-span steel pipe fore-piling, prelining (Fig. 2), etc., are likely to yield highly effective results. Since special construction equipments are required, however, these methods are adopted only in cases where extremely poor ground conditions continue over a long working section or the settlement of the surface ground is severely restricted.

Among the long-span steel pipe fore-piling methods, a method which uses a conventional drilling jumbo has been developed. It is often used at the portal or at fractured zones due to its simplicity in application (Fig. 3).
1.6.2. Stabilizing the cutting face

There is a method which forces the cutting face to stand alone by subdividing the face. However, since such poor ground conditions require long-span rock bolts or the early closure of the cross-section, a large cutting face is necessary. Thus, stabilization by means of auxiliary methods has become popular in recent years.

Face shotcrete and face bolts can be added during a conventional working cycle and are easily employed. Injection methods are used to improve the mechanical properties of the ground; cement or urethane is being applied nowadays. In some cases, a long bolt or a cable bolt is first inserted ahead of the cutting face; the bolt is then cut down while the excavation is being carried out.

1.6.3. Methods to counteract water inflow

Drainage methods such as drainage boring and drainage tunnels are applied as countermeasures. For non-cemented soil grounds in particular, underground water may cause the ground to liquefy, leading to a difficult construction. For this reason, well-point drainage and deep wells are often constructed.

In cases where there is an exhaustible amount of underground water, like in undersea tunnels, wherein if drained, the surrounding ground may settle, a cut-off method is applied. Grouting is the main method, however, and its technology has been developed through
1.7. Construction method

1.7.1. Excavation

Excavation methods are divided into two types, namely, excavation by drilling and blasting, and excavation by machines. Fig. 4 shows the percentages for the usage of each method. For soft rock and weathered rock, mechanical excavation using a boom type of excavation machine are conducted. However, high capacity excavation machines are coming into wide use and for ground with uniaxial compressive strength up to 40 MPa. Some machines can complete the excavation faster than by drilling and blasting.

Noise and the vibrations associated with blasting have an influence on both human beings and buildings. A promising excavation method, based on the prediction equation of the transmission of vibrations and test blasting, is under consideration. In some cases, the use of explosives is not allowed. For a boom type of excavation machine, a model machine which can deal with rock that has a uniaxial compressive strength of 80–100 MPa has been developed. For harder rock, the rock-split method and the special machine have been developed.

1.7.2. Excavation methods

The area of the cross-section, excavated at one time, is determined by stability of the cutting face. The capacity of excavation machines should be taken into account. But the method should be planned according to which method is suited for most of the ground in question and that the local instability of the cutting face can be reinforced by auxiliary methods. As shown in Fig. 5, the bench cut method is presently the most popular method. However, the full-faced excavation method with benching is approaching half the number.

1.7.3. Development of high efficient excavation methods

For large-scale construction works, there are some cases in which special purpose machines are employed to improve the efficiency. With the blasting method, a gantry jumbo is sometimes utilized for this reason. For soft rock, a specially mechanized excavation system which named TWS was developed and adopted to the San-nou Tunnel. New technologies such as quick-hardening mortar and spherical cutting face for full-faced excavation, were employed.

1.7.4. Muck transport method

The work of carrying the muck soil out of the tunnel is generally done with a tractor shovel and dump truck system. In order to shorten the work time and to reduce the ventilation, a large-scale dump truck or the temporary placement of container is adopted. For tunnels which have small cross-sections or are long, a rail type is adopted.

A belt conveyor type has been developed in which it is easy to extend the belt as the cutting face advances; it is adopted when using a TBM. In some construction sites of the Shinkansen tunnels, the belt conveyor type was combined with a movable crusher.
1.8. Special ground conditions

1.8.1. Grounds with swelling

It is often the case that when a tunnel excavation is conducted, rocks exhibiting swelling are encountered, such as relatively new sedimentary rocks like mudstone and tuff, and hydro-thermally altered rocks.

In the early stage of applying the support system to a swelling ground in Japan, using shotcrete and rock bolts, a contractible mechanism was designed on some occasions with a large number of long rock bolts. From research conducted afterwards, importance should be placed on the early closure of the cross-section of the tunnel by electing a highly stiff support system which can minimize the loosening of the ground and reinforce the cutting face in the case of a swelling ground, since the stability of the cutting face is poor and leads to excessive deformation.

An example is shown in Fig. 6. This approach is applied for heading and temporary upper bench inverts for reinforcement of the cutting face and the early closure, to tunnel in ground of very large swelling.

1.8.2. High water pressure and a large amount of water inflow

Predictions should be made before the situations get too serious and it becomes necessary to adjust the conditions so that the tunnel can be constructed by employing auxiliary methods such as drainage or cut-off.

1.8.3. Non-cemented soil ground

In the case of a sandy ground, it can be liquefied or the cutting face becomes unstable due to water inflow. When the content of clay and silt is low, less than 10%, and the uniformity coefficient is low, less than 5%, the ground is possible to become liquefied.

In the case of a clayey ground, an increase in the water content tends to decrease the strength. Since the bearing capacity is generally not large and it deteriorates especially when affected by water, caution should be taken.

1.8.4. High earth temperature, hot springs and toxic gas

Many parts of Japan are located in volcanic belts, and tunnels sometimes encounter high temperature and hot springs.

Toxic gases, such as inflammable gases like methane gas, oxygen-deficient air, etc., are sometimes encountered.

1.8.5. Rock bursts

Rock bursts occurred in the Shimizu Tunnel and in some other tunnels. There is a case in which a rock burst even took place with an overburden of approximately 300 m. Rock bursts are not easy to predict, but investigation using acoustic emission is sometimes recommended.

1.9. Neighboring tunnels

Generally speaking, a neighboring tunnel is designed by considering the mechanical influence through an
analysis. Since the ground is also affected by both tunnels, plastic zones may have to be expanded. Thus, proper countermeasures need to be taken through the adoption of auxiliary methods. An example of twin-tube tunnels is shown in Fig. 7.

2. Tunnels with large cross-sections

2.1. Plan and design of the New Tomei-Meishin Expressway tunnels

In Japan, the number of tunnels with large cross-sections of approximately 130 m², is increasing due to the increasing demand for three-lane road tunnels.

The New Tomei-Meishin Expressway is the second expressway connecting three major cities in Japan, as shown in Fig. 8. They are high-standard roads with six lanes and a speed limit of 140 km/h. Since there are many sections along the route which pass through mountains, tunnels account for 25% of the total length of the route. Taking into account a balance between the stability of the tunnels and the economic issues, in addition to accommodating the building limits of having a three-lane road and sufficient shoulders, a tunnel with a large, flat cross-section and an excavated area of approximately 190 m² is planned, as shown in Fig. 9.

The first work section of 370 km, out of a total length of 502 km, is under construction. There are 167 tunnels in this work section which account for a total tunnel length of 224 km.

2.2. Design of the supports and the lining

A new standard pattern of supports was set, as shown in Table 1, by feeding back the measurement data taken during the test construction.

a. Since the settlement of the crown has a flat cross-section, it surpasses the others, and the horizontal convergence is small. The ground displacement runs deep at the crown, while it occurs near the surface at the side wall. For this reason, the supports are mainly used to help prevent a drop in the ground at the crown.

b. In order to provide early supports to prevent ground deformation, high-strength shotcrete was adopted. The strength of the high-strength shotcrete was set at double the strength of the standard shotcrete, and the design thickness of the shotcrete was made thin. The strength at an early stage of curing was also important, so it was specified.

c. In addition to thinning out the shotcrete, a high-standard steel, which was light and easy to handle, was used for the supports.
Fig. 9. Tunnel cross-section.

Table 1

<table>
<thead>
<tr>
<th>Ground class</th>
<th>Cut per advance (top heading) (m)</th>
<th>Rock bolt Length (m)</th>
<th>Peripheral Upper Bench</th>
<th>Longitudinal</th>
<th>Steel arch support</th>
<th>Thickness of shotcrete (cm)</th>
<th>Thickness of lining (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>2.5 (2.0)</td>
<td>4 4</td>
<td>3.0 (2.0)</td>
<td>3.8 (2.0)</td>
<td>– –</td>
<td>10*</td>
<td>40 –</td>
</tr>
<tr>
<td>CI</td>
<td>2.0 (1.5)</td>
<td>6** 4</td>
<td>1.5 (2.0)</td>
<td>2.9 (1.5)</td>
<td>– –</td>
<td>15*</td>
<td>40 55</td>
</tr>
<tr>
<td>CII</td>
<td>1.5 (1.2)</td>
<td>6** 4</td>
<td>1.3 (1.6)</td>
<td>1.8 (1.2)</td>
<td>H-154 H-154</td>
<td>20</td>
<td>50 70</td>
</tr>
<tr>
<td>DI</td>
<td>1.2 (1.0)</td>
<td>6** 6</td>
<td>1.3 (1.6)</td>
<td>1.4 (1.0)</td>
<td>H-154 H-154</td>
<td>20</td>
<td>50 70</td>
</tr>
</tbody>
</table>

( ) means without TBM pilot advance. Shotcrete is the high strength type, *upper section uses SFRS (steel fiber reinforced shotcrete. Rock bolt: ** has strength of 2901, others have strength of 180 kN. Steel arch support is high grade type.

d. For the grounds with a classification of Class B, in which the arched section was relatively self-supporting, steel fiber reinforced concrete was adopted as the shotcrete in the upper-half section and steel supports were omitted.

e. Since a large number of long rock bolts were required for the arched section, high-strength rock bolts were adopted.

f. The designated standard strength of the lining concrete was increased and its thickness was reduced.

2.3. Consideration of the construction method

Based on the results of the pilot construction, the TBM drift method was adopted for long tunnels. For the other tunnels, the central top heading method was
adopted, depending on the stability of the cutting face and the crown.

A TBM, with a diameter of 5 m in the upper-half section, was adopted as the drift. The results of the pilot construction led to the following outcome:

a. The cutting face was stabilized and the geology ahead of the cutting face was confirmed; thus, an efficient construction was possible. Judging that the excavation length could be lengthened, compared with the top head method, it was adopted as the standard design.

b. For poor ground, reinforcements using cable bolts were adopted from the inside of the tunnel preceding the enlargement excavation of the upper-half section (Fig. 10).

c. Detailed geological investigation were conducted in the tunnel. For tunnels in hard rock, it is under investigation whether or not an appropriate and economical design is possible through the investigation of discontinuities and by applying a key block analysis.

3. Urban tunnels

3.1. Introduction

Most large cities in Japan stand on new deposits or fills near coasts. For this reason, many tunnels built in urban areas in the past were constructed by the shield tunneling method or the cut and cover method.

From the viewpoints of cost efficiency and the flexibility of the cross-section design, the range in applications of the mountain tunneling method to urban areas is expanding. So far, it has also been applied to Pleistocene deposits, and the JSCE specification states that it is applicable to non-cemented grounds when the uniaxial compressive strength is greater than approximately 0.1 MPa and the deformation modulus is greater than approximately 10 MPa (JSCE, 1996). There have been cases in the past for which it was used for weaker grounds.

3.2. Design of the supports

In designing the supports, attention should be paid to the stability of the cutting face and to making sure that a negative influence, such as surface settlement, is not exerted on the surrounding environment. For this reason, high-strength support elements should be applied which consist mainly of steel supports and shotcrete.

In many cases, the design patterns are tentatively set by referring to standard design methods and examples of similar construction works, and then are finally set after considering the analysis results of FEM, and other numerical methods.

3.3. Design of the lining

In most cases, the thickness of lining, and the amount of reinforcement, are determined by analysis, setting up the external forces such as earth pressure, water pressure, future variations in load, etc.

3.4. Excavating method

The most important consideration in selecting a method of excavation is the stability of the cutting face. In the case of sandy grounds, which are susceptible to liquefaction, a subdivision of the cutting face may be chosen. Recently, the number of cases in which the excavation is done with a large cutting face and auxiliary methods has increased. This is because such methods have been made possible through the advancement of auxiliary methods, which have enabled the pursuit of using large construction equipment, shortening the construction period and increasing cost efficiency.

3.5. Stabilization methods

Stabilization methods are adopted to ensure the stability of the cutting face and to minimize the influence of construction on the surrounding environment.

In the case of non-cemented soil grounds, underground water often affects the stability of the cutting face and the bearing strength of the grounds. In those cases, it is necessary to employ appropriate methods such as dewatering and cut off.

There are many examples of conducting fore-piling ahead of the cutting face in order to stabilize the crown and to control the surface settlement. Fore-piling work ranges from simple fore-poling to fore-piling which has a significant effect such as long steel-pipe fore-piling, pipe roofing, horizontal jet grouting, prelining, etc., but the scale is influenced by the stability of the ground.

In many cases, countermeasures are determined by referring to past examples. When analyzing many past examples, criterion should be based on the terms of the deformation modulus of the ground.
3.6. Measurement and management

For urban tunnels, it is important to ensure the safety of the construction work because there is significant influence if an accident such as roof-fall takes place. The influence on the surrounding environment is also significant, and thus, it is necessary to monitor the state rigorously during construction.

Sakurai (1998) and Sakurai et al. (in press) proposed a management method using limit strain; it uses a back analysis by FEM to grasp the strain around a tunnel. Moreover, the back analysis by FEM is also used to obtain the mechanical constants of the ground during construction and when considering design modifications. For shallow tunnels, a loosened zone forms above the tunnel and a so-called ‘accompanied settlement’ is often observed. That is, the settlement of the ground surface becomes almost the same as that of the crown of the tunnel.

3.7. Latest examples of mountain tunnels in urban areas

3.7.1. Narashinodai Tunnel (Toyo Railway Express Line)

An excavation method was adopted which placed importance on the early closure of the supports. It was named the CRD (cross-diagram) method (Fig. 11).

3.7.2. Maiko Tunnel (Honshu-Shikoku Connection Highway)

High-rise buildings and other structures exist near the ground surface; thus, the settlement of the ground surface was severely restricted. There was little underground water, and long steel-pipe fore-piling was adopted (Fig. 12).

3.7.3. Hodogaya Tunnel (Yokohamashindou)

The enlargement work which expanded 2×2-lane tunnels to 2×3-lane ones was done under heavy traffic conditions, average traffic volume of approximately 140,000 vehicles per day. It was necessary to control the surface settlement and not to affect a nearby service
3.7.4. Ohme Tunnel (Metropolitan Central Highway which constitutes Tokyo’s loop road)

It was built as a two-layer structure so that a street, 16 m in width, could be accommodated below it. It is a tunnel with a large cross-section with an excavated area of 230 m². The excavation work was done in four steps, starting from above. For stabilization of the upper-half section long steel-pipe fore-piling was used. To maintain the stability of the side wall, the excavation was carried out by placing the secondary lining after excavating the upper-half, and then excavating the lower-half (Fig. 14).

4. Application of Tunnel Boring Machines (TBMs)

4.1. Present state of TBMs in Japan

TBMs were first introduced in Japan in 1964, and were adopted for the Seikan Tunnel and approximately 30 other tunnels built from 1965 to 1975. There were only a few long tunnels for which it was concluded that the TBMs would not be suitable due to the type of ground. However, the use of TBMs has increased again by using newly developed technologies.

4.1.1. Waterway tunnels

There are many cases in which waterway tunnels were constructed in horizontal tunnels for electric power generation, sewage, irrigation channels, etc. Many tunnels have small cross-sections, but there are also tunnels with large cross-sections such as the Akiba Third Diver-sion Channel (ϕ = 7.1 m, pilot and reaming method).
Fig. 15. TBM pilot of the tunnel along the New Tomei-Meishin Expressways.

4.1.2. Road tunnels

In 1991, a TBM with a diameter of 5.0 m was adopted in the drift excavation of the Maiko Tunnel. Then, in the construction of tunnels with large cross-sections along the New Tomei and Meishin Expressways, TBMs with a diameter of 5.0 m were adopted for advancing the drift excavation (Fig. 15). A tunnel with a length of more than 3 km, which temporarily faced oncoming traffic, was equipped an emergency tunnel in which a TBM with a diameter of 4.5 m was employed. There is a plan for full-faced excavation, by means of a TBM with a diameter of 12.8 m, for the Hida Tunnel along Tokai Hokuriku Expressway.

4.2. Selection of a TBM

In Japan, either the open type or the double-drum shield type is chosen depending upon the ground conditions. For a tunnel with a large cross-section, an improved open type TBM, which maintained the cost efficiency of the open type and has the possibility for support work inside the shield and advancement by shield jacks, was developed and applied to the Hida Tunnel.

4.3. Tunnel supports

For supports with small to medium diameters, high-early-strength shotcrete mortar is often used; it is used together with steel supports in the case of a collapsible ground or a large load. In locations where the collapse is severe or advancement by a gripper is difficult, steel liners are used. In waterway tunnels, a method of completing the lining at the same time as the excavation, using precast segments or ECL method, is adopted.

4.4. Muck transport

For a tunnel with a cross-section diameter smaller than 2.5 m, liquid transport is the primary transport method. For a tunnel with a larger cross-section, however, rail and successive belt conveyor types are often used. Recently, a successive conveyor type has become popular along with the primary transport method.

4.5. Problems with the TBM method

TBMs have not yet been able to overcome all the Japanese ground conditions. Some problems still remain, such as finding countermeasures against poor grounds, their applicability to tunnels with large cross-sections, etc.

The following research and investigation works are being undertaken.

a. A geological investigation ahead of the cutting face was carried out by pilot boring, by simple seismic
wave exploration, and by the drilling hole energy method, etc. With accumulating more experience, the accuracy should be improved.

b. TBMs capable of driving through rather poor grounds should be developed.

c. A simple stabilization method to improve the ground beforehand and also a machine with good workability for stabilizing ground should be developed.

d. Methods for avoiding problem by monitoring the state of the operations, and TBM operating methods which do not generate problems should be investigated.

5. Closing remarks

This paper has introduced the present state of design and construction technologies for the mountain tunneling method in Japan. At present, research and development are being conducted to overcome technical problems. The development of construction technology of high-quality tunnels under various difficult conditions, is anticipated.

References


