

## Shield Tunneling Method

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### **Summary**

#### **Innovation**

At a time when engineers around the world were groping for a reliable way to stabilize tunnel faces, it was the innovative idea of using excavated soil that led to success, leading to the development of a key tunneling technology.

#### **Effectiveness**

Shield tunneling is the excavation method best suited to conditions in Japan, where space is short, soft alluvial deposits are widespread, and the demand for tunnels is high. Developments in shield tunneling have contributed greatly to urban infrastructure development in this country.

#### **Impact**

Japan's expertise in construction and management technology is highly regarded around the world. Our technology is employed in Asia, the U.S., Europe, and the Middle and Near East. It has even been transferred back to the River Thames in London, the birthplace of shield tunneling.

### **Background to the development of shield technology in Japan**

Modern urban development in Japan had to begin with recovery from the ruins of war. In this small, highly populated country, an enormous amount of urban development work needed to be carried out under far from ideal conditions. With rapid economic growth, socioeconomic activity came to be excessively centralized in urban areas, leading to difficulties in securing space for urban facilities. As a result, they have often had to be built in already developed areas, often heavily built-up areas with dense concentrations of houses on narrow roads. Moreover, most major Japanese cities are situated on soft alluvial ground, through which tunneling is technically difficult.

The cut-and-cover method is the most common and economical way of building tunnels with a relatively

small overburden. However, it has a serious impact on vehicular traffic and local residents. Prior to carrying out cut-and-cover work, particular attention must be paid to this impact, and this is often the cause of delays with the work. For this reason, efforts have been made to avoid this method when constructing tunnels in urban areas.

There has also been rising demand for deeper tunnels, as utilization of underground space has risen. This also has led to a search for other methods besides cut-and-cover. In soft alluvial ground, shield tunneling methods are the obvious choice. This active demand for tunnel construction, boosted by slow development of the urban infrastructure and difficult social and natural conditions, has honed Japan's shield tunneling technology to a level where it leads the world.

### **Origin of shield tunneling and first-generation technology**

Shield tunneling was developed as a method of digging tunnels through the soft ground below rivers. The story of Brunel hitting upon the idea when he saw a shipworm boring holes through the bottom of a ship. He was granted a patent in 1818, and commenced constructing the Thames Tunnel in London in 1823. His basic concept was to press a rigid frame (shield) forward through soft ground with jacks, thus preventing the ground from collapsing, and build the tunnel structure within the frames. By repeating the process of jacking then constructing the support structure, the tunnel would move forward.

The shield use for the Thames Tunnel was rectangular in cross section. A later redesign, with a circular cross section, was used by Greathead to construct the Tower Subway in 1869. Cast steel segments, backfilling, and injection were all used by Greathead in his shield work, so his was the prototype of today's shield. The use of compressed air was studied for work on the Woolwich Tunnel beneath the River Thames in 1876, although it was not actually used until the end of the work. Greathead also conceived plans for using water to

excavate soil and for the stabilization of the face.

As this makes clear, the first generation of shield tunneling technology was developed about 150 years ago. Thereafter, no great advances were seen in the technology until the 1960s; this plateau lasted for about a century until a sudden quantum leap, led mainly by Japan.

### **Worldwide struggle to stabilize the tunnel face**

The biggest problem with the shields of the late-19th and early-20th centuries was that there was no reliable means of stabilizing the face. A great deal of effort was concentrated on overcoming this shortcoming in the 1960s. We first look at the work that went on overseas.

Workers in pneumatic caissons are protected from so-called "caisson disease" by supplying the required compressed air to the working face only. This is made possible in tunneling work by installing a bulkhead at the front edge of the shield to isolate the face from the tunnel interior. This design is called a closed shield. The first shield of this type was used in Berlin in 1899. However, because excavation was manual, it remained necessary for workers to operate in the compressed air chamber. So although working conditions in the rest of the caisson were improved, the fundamental problem of the pneumatic caisson remained unsolved. Still, the idea of taking the necessary measures to close off the face was very important. A shield of similar type was used in Paris in 1962, though this one was designed to allow excavation from the rear of the bulkhead using hydraulic equipment. However, problems such as air blows could not be resolved so long as compressed air was used.

In 1967, a shield that used a slurry of excavated soil and water instead of compressed air was developed in France. Excavation was by reciprocating cutters, and excavated soil and slurry were discharged through piping for disposal. This was basically the same mechanism as used for present-day slurry shields. After being used in France, this shield was sent to Mexico City, but its performance was poor and no further improvements were made. A slurry shield called a bentonite shield was developed and tested in the U.K. in 1972. The design was used later for the construction of trunk sewer tunnels in 1976. However, because the shield was not suited to the soil conditions, its performance in the project was bad, and this type of shield has not been used since in England.

A shield known as the hydro-shield was developed



Photo 1. Earth pressure shield

and used for sewerage work in Hamburg, Germany, in 1974. This also was basically a slurry shield, but it was provided with a compressed air chamber near a bulkhead to prevent the sudden pressure fluctuations at the tunnel face associated with losses of slurry. This type of shield then has widely used in the area.

### **Rapid technological development in Japan**

In Japan, shields of the conventional open type were used in construction of the Kakuoan Subway in Nagoya in 1960, and the Shakujii River Trunk Sewer in Tokyo in 1962. At this point in time, Japan lagged other countries in the development of shield tunneling technology. However, with increasing demand for tunnels and the need to overcome hostile conditions, research related to shield development became more active. In 1963, a mechanical shield was used for the construction of a water main at Oyodo in Osaka. In 1964, slurry was used to stabilize a tunnel face, although pipe jack excavation method was adopted. In 1969, a slurry shield 7.3 m in diameter was used to complete a tunnel for the Keiyo Line underneath the Morigasaki Canal. This shield diameter was a world record at the time. In 1972, an earth pressure shield was developed, marking Japan's coming of age in the world of tunneling. Having been behind in the early 1960s, Japan was making rapid strides of its own by the latter half of the decade.

#### **(1) The challenge of tunnel face stabilization**

The main issue driving innovation in shield tunneling technology in the 1960s was the problem that had faced conventional shield work since the early days: how to control the unstable tunnel face. The solution to



Photo 2. Slurry shield (used for the Tokyo Bay Aqualine)

the problem was to install a bulkhead behind the face and inject into the resulting space a material that could stabilize the cut face. A bentonite slurry, as used for cast-in-situ diaphragm walls and oil wells, offered particular advantages in this role. A shift from open shields to closed designs was the natural result.

Once the shield is closed in this way, manual face work becomes impossible, so mechanization of excavation and muck removal became a necessity. Further, the hydraulic pressure of the slurry on the face acts on the tail void section of the shield. Accordingly, preventing the leakage of pressurized soil and water from the clearance between shield and segment became a driving concern. The device used to prevent such leakage is called a tail seal. In addition, earth seals are needed to protect the rotating parts of machinery from soil intrusion, and these also form an important element in shield technology.

As this demonstrates, the most crucial requirements in developing the closed shield were suitable materials for stabilizing the face, mechanical excavation methods, systems for discharging and removing excavated soil, and the tail seal. Face stabilization is possible with slurry or excavated soil, and a shield using the former is known as a slurry shield. Slurry was an obvious first choice, as noted above, and its use was pioneered in France, the U.K., and Germany. In Japan, full use has been made of the slurry shield since 1969, almost in concert with its use elsewhere. The slurry shields developed in Japan are characterized by the use of fine matter in the excavated soil, with the addition of auxiliary materials such as clay, to obtain a slurry with suitable stabilizing and discharge properties. This achieves very cost-effective slurry preparation.

This idea of using excavated soil to stabilize the face is unique to Japan, and is a technology to be proud of.



Photo 3. Wire brush tail seal

The technology began with the earth-pressure shield, in which a screw conveyor discharges the soil excavated with a cutting head. This is essentially an extension of the mechanized shield, rather than a slurry pressure shield. To make use of the excavated material to stabilize the face, it is necessary to make it plastic so as to exert a controlled pressure on the face, while also ensuring that it is suitably superplasticized for ease of discharge from the face. Further, it is necessary to incorporate a mechanism for discharging the soil through the bulkhead, across which there is a pressure gap. In practice, the slurry is formed by mixing soil with additives such as bentonite in an agitator. A screw conveyor is used to remove slurry from the face. The conveyor is also used to control the pressure at the face. A full-scale shield equipped with all of these mechanisms was used for the construction of 2.44 m sewer main in Katsushika Ward, Tokyo, in 1976 (Photo 1). This method of tunneling later grew into one of the mainstays of shield tunneling, ranking alongside the conventional slurry shield (Photo 2). In 1981, a modification involving the use of foam as an additive in the slurry was developed; this is known as the foam shield.

## (2) Tail seal, backfilling, and water cut-off seal

Tail sealing is a key part of closed shield technology. The seal slides over the tunnel segments, and so must exhibit a high level of durability. First attempts were urethane lip-type seals, but their performance was unsatisfactory. A wire brush seal was developed around 1973, and this enhanced cut-off performance and durability at high pressures (Photo 3). Water cut-off and lubrication are achieved by supplying a special greasy compound mixed with fibers to the seal, which is shaped like a brush of steel wires. With later improvements,





Photo 4. Holding-type master and slave shield

this type of seal achieved a high level of stable performance by the first half of the 1980s. It is the development of this seal that provided a foundation for the development of modern shield technology in Japan, and this seal is used for almost all shields today. It has been said that the Japanese thatched roof was the inspiration behind this innovation.

To ensure a good seal at the tail section of a shield, the tunnel segments must be accurately fabricated and assembled. This requirement has driven up the precision of segment construction in Japan. In recent years, accuracy has been increased still further by the use of robots in the assembly process, and by carefully considering the joints between segments. One development made in Japan is to apply a sealing material to the four joint faces of segments so as to cut off water at the primary lining. A suitable water-swelling sealant was developed in 1980. In combination with accurately fabricated segments and increased assembly accuracy, this has helped maintain a high level of water cut-off performance.

Backfilling of the tail void is an important requirement to prevent ground subsidence and ensure stable shield advancement. The invention of a system by which backfilling takes place as the shield is advanced, along with a new thixotropic backfilling material (a material that softens once but recovers its strength with time), has made shield tunneling work more reliable.

For reasons of space restriction, tunnels in Japan are often required to make a sharp turns. To meet this demand, shields equipped with a articulation have been developed.

### **(3) Total control technology and return of the shield to its birthplace**



Photo 5. Insert-type master and slave shield

Shield tunneling suffers setbacks even with the best preparation of machinery and materials. Technology for shield advance control is particularly important in minimizing problems. Further, the maintenance of a stable face relies on careful control of slurry or earth pressure while adjusting the balance between excavation volume and discharge to prevent overbreaking. One of the characteristic features of shields developed in Japan is that they are fully equipped with sensors, and advance is controlled by computer. An impressive track record testifies to Japan's highly developed control techniques, including the fully automated operation of shields.

The shield tunnel part of the Tokyo Bay Aqualine highway, which commenced in 1989 and was completed in 1997, is the culmination of Japanese shield development since the 1960s. To ensure the success of this enormous project, a complete system was established, encompassing not only the shield tunneling machine itself, but also the rear-mounted equipment for processes such as the automated assembly and delivery of segments. Indeed, the best of all available technology was brought together to complete this project.

There are many examples of Japanese shield tunneling technology being employed in Asia, such as for sewerage work in Bangkok in the latter 1970s, and it later found application in the U.S., Europe, the Middle East, and Near East in the 1980s. When a Japanese earth pressure shield machine was used to successfully complete a tunnel in San Francisco, the U.S. tunnel construction industry was astonished at its performance. Four Japanese shields were used for construction of the Channel Tunnel between the U.K. and France. Thus, Japanese shield tunneling technology gained an excellent reputation during the 1980s. The overseas use of Japanese tunneling technology is perhaps best exempli-



Photo 6. Typical rectangular shield used for the MMST method

fied by work for the Docklands Light Railway in London, when a Japanese contractor carried out shield tunneling work underneath the River Thames. Thus, technology that evolved in Japan was returned right to its birthplace under the Thames in London.

### Further advances

Almost all problems related to the "face" end of closed shield tunneling had been overcome by the time the Aqualine tunnel was constructed. As a result, the shield method is now able to operate under a wide range of soil conditions. Still, there remains room for improvement, such as in the ability to drive a tunnel through gravel layers. The next challenge is to increase cost efficiency and adapt the method to suit difficult construction conditions beneath urban areas.

In recent years, the basic technology developed by

the 1980s has been carefully examined and a wide variety of derivatives have come into use. Chief among these are the following: overlapped-double-circular cross-section shields, called MF or DOT; oval and rectangular cross-section shields; master and slave shields (Photos 4 and 5); outer hull advance shields, such as MMST (Photo 6); and even a spherical shield capable of boring both vertical and horizontal shafts. As yet, these shields have yet to be used overseas, indicating that Japan's tunneling technology is particularly advanced.

To increase cost efficiency, it is not only face technology that is important, but also that of the rear sections of the tunneling equipment. Consequently, recent emphasis has been on developing the rear section, such as techniques for the assembly of segments and effective use of excavated soil. Segment assembly is a large proportion of the work involved in shield tunneling, accounting for about 40% of the total effort. To rationalize the assembly of segments, special segment geometries and joints have been developed. The use of in-situ concrete instead of segments, in a method known as ECL, has also been pioneered.

Further, the ability to drive extremely long tunnels and speeding up the advance of shields are considered important challenges. Shield tunneling work has been carried out over distances of a few kilometers or more, and a shield capable of advancing while segment assembly takes place has become available.

The combined efforts of many people and the great demand for tunnels in Japan have driven Japanese tunneling technology into the leading position in the world. But with urban facilities in our major cities still needing considerable improvement, there will be future demand for tunnel excavation under harsh conditions. Now that the Law Concerning Special Measures for Public Use of Spaces Deep Under Ground is in place, we have a regulated system for using our underground space. This will surely lead to further improvements and refinements to shield tunneling, including technology for ultra-deep subterranean tunneling.