A History of Railway Tunnels in Japan

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Introduction

Only about 30% of Japan's land area is flat with the remaining 70% being mountainous. The cities on the flat land have well-developed subway systems with many railway tunnels. As of 2013, 3813 km of Japan's 27,497 km of railway lines (approximately 14%) is in tunnel.

The three main methods for constructing railway tunnels are mountain tunnelling, shield tunnelling, and open cut (cut-and-cover) tunnelling. Other methods include immersed-tube tunnelling and caisson tunnelling. Early railway tunnels in Japan used technologies from abroad, but eventually the nation developed its own technologies. Tunnel construction in Japan often faced difficulties due to the complex geology, but technical improvements were made by using feedback from each tunnelling experience. This article looks back at the advancement in railways and the progress in Japan's tunnel technologies.

History of Railway Mountain Tunnelling

Japanese tunnels before railways (prior to 1870s)

It is unknown when the first tunnels were dug in Japan—the same is true for tunnel history worldwide. Tunnelling in earnest as civil engineering started during the Edo period (1603–1868) with a record of a tunnel for the Tatsumi Aqueduct (Ishikawa Prefecture) excavated in 1632. This 3.3-km long, 1.5 to 2.1-m wide, 1.8-m high tunnel was dug through easy geology, so it was completed in just 9 months. Drifts were dug during construction to confirm the tunnel position and secure ventilation, and lighting was by oil lamps. In 1666, the 1.3-km long, 2-m high, and 2-m wide Hakone Aqueduct Tunnel (located between Kanagawa and Shizuoka prefectures) was dug over a span of 4 years.

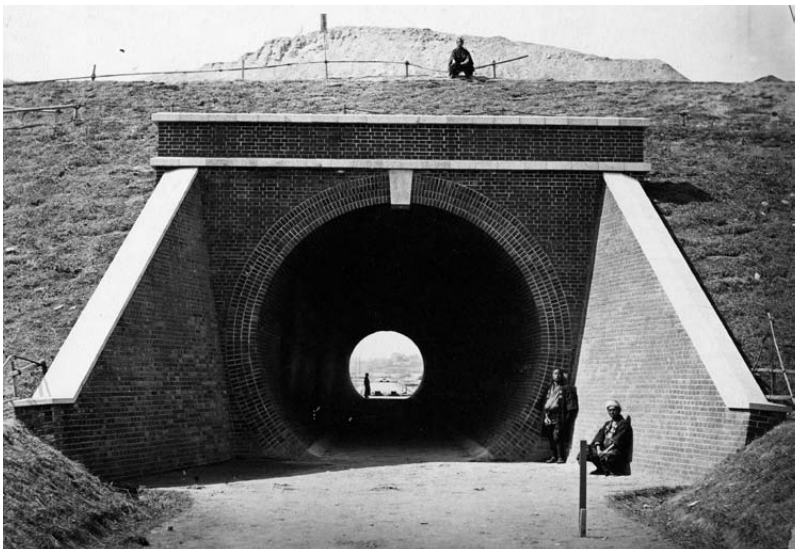
The 180-m long Aonodomon (blue tunnel) at Yabakei Gorge (Oita Prefecture) was completed in 30 years from 1720 to 1750. It was Japan's first tunnel for transport purposes and was purportedly dug by the monk Zenkai (1691-1774).

Techniques for mining ore also advanced in the Edo period, and specialist miners performed excavation work at mines.

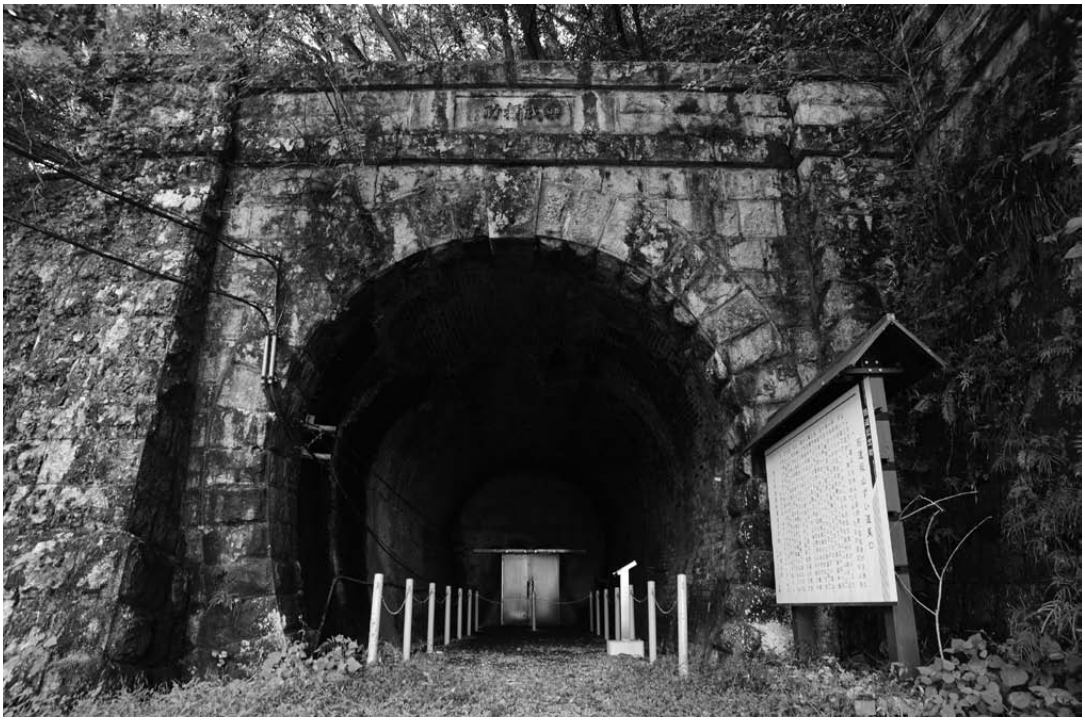
Introduction of modern tunnelling technologies (1870s to 1900s)

Railway tunnels were the starting point for modern tunnelling technologies in Japan. The first railway line built in Japan in 1872 between Shimbashi and Yokohama had no tunnels, and the first tunnels were built on a section of track between Osaka and Kobe opened in 1874 passing under a high-bedded river flowing from Mt Rokko. Three short tunnels—the 111-m long Ashiyagawa Tunnel, 50-m Sumiyoshigawa Tunnel, and 61-m Ishiyagawa Tunnel—were constructed by the cut-and-cover method under the supervision of a British engineer. All were later changed to aqueduct bridges around 1920, so the tunnels are no longer used.

This was followed by the 665-m Osakayama Tunnel constructed from 1878 to 1880 between Kyoto and Otsu. This tunnel was built by Japanese engineers alone, without using foreign advisors due to the intention of Masaru Inoue Director of the Railway Board to promote domestic railway technologies. Miners were called from Ikuno silver mine and traditional mining techniques and stonemasons were



Ishiyagawa Tunnel (1874) (Japan's first railway tunnel) (Author)



Osakayama Tunnel built solely by Japanese engineers (1880) (now preserved as railway memorial) (Author)

used. With the completion of Osakayama Tunnel, tunnelling in Japan made an early departure from the techniques of foreign engineers. In 1884, the 1352-m Yanagase Tunnel on the Hokuriku Line was completed as Japan's first tunnel longer than 1 km. An overview of its construction is reported in the Minutes of Proceedings of the Institution of Civil Engineers by Kinsuke Hasegawa.

Early tunnels were built mainly using a construction method called 'Japanese excavation' where tunnels were advanced at a top heading first. Construction was easy using this method, so it was employed for most railway tunnels constructed until around 1920. Attempts to shorten the construction period by using vertical shafts were made at an early stage in works such as the 928-m Kabuto Tunnel on the Kansei Railway (Kansai Line today) completed in 1889, the 1629-m No. 2 Itayatoge Tunnel on the Ou Line completed in 1894, and the 2656-m Kamuriki Tunnel on the Shinonoi Line completed in 1896. The Kamuriki Tunnel was Japan's first railway tunnel longer than 2 km.

The 4656-m Sasago Tunnel on the Chuo Line completed in 1903 became Japan's longest tunnel until completion of the Shimizu Tunnel on the Joetsu Line in 1931. The Sasago Tunnel excavation used electric locomotives to remove spoil and it was the pinnacle of tunnel construction in the Meiji period (1868–1912). A hydroelectric power plant was built near the worksite, providing power for electric locomotives, lighting, and fans and contributing to more efficient construction and a better construction site.

Progress in tunnel construction (1910s to 1920s)

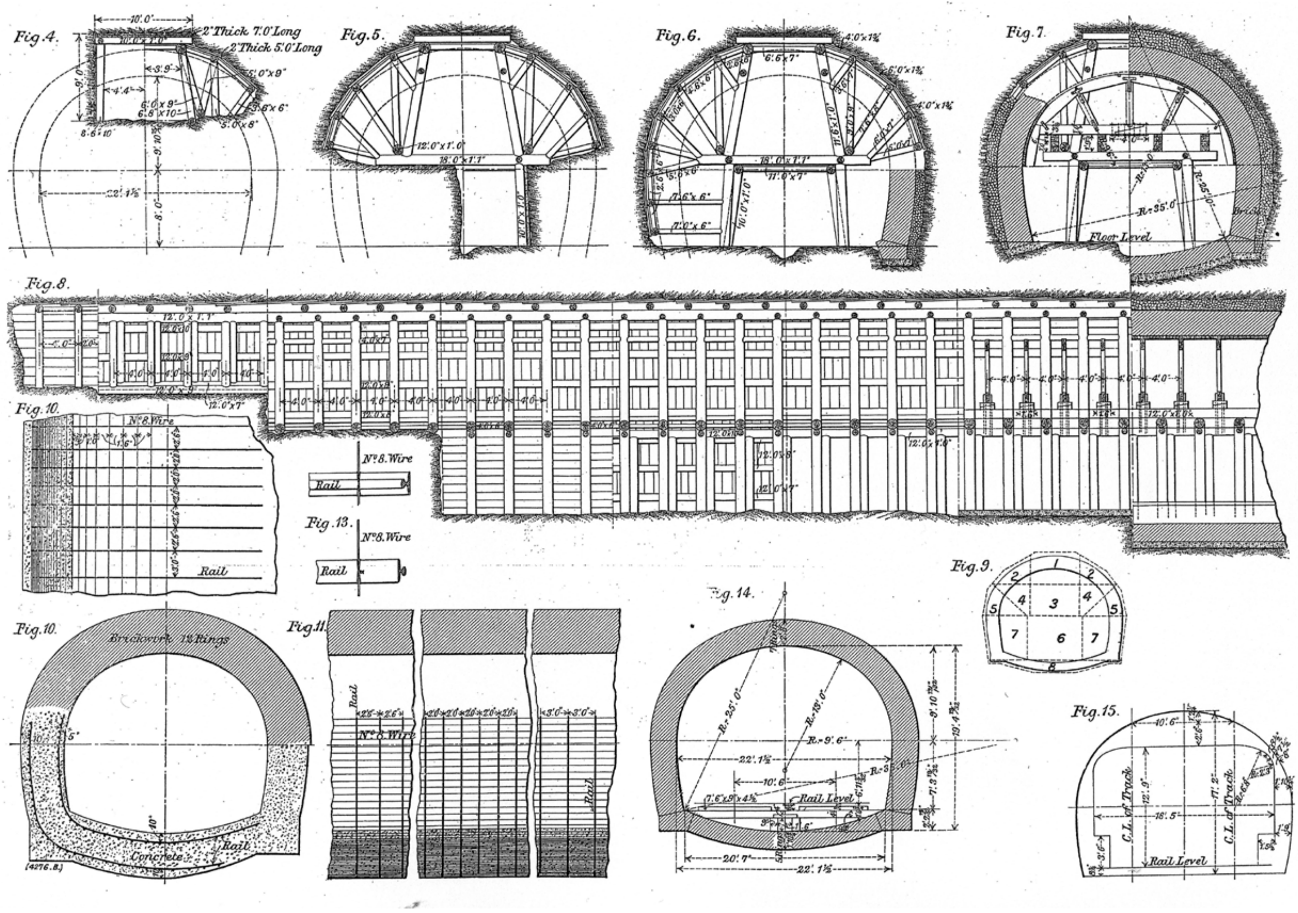
Little progress in tunnelling technologies was made for some period after the Sasago Tunnel, until the age of long tunnels arrived in the 1910s because construction of trunk lines had eased off with construction of mountain routes and improvement to grades.

The first Tokaido main line route between Otsu and Kyoto constructed in 1880 bypassed Mt Osaka to the south where the Osakayama Tunnel was constructed; the 1865-m Higashiyama Tunnel and 2325-m Shin-Osakayama Tunnel were completed subsequently in 1921 to relieve the steep grade and shorten the route.

The steep grade on the Tokaido main line between Kozu and Numazu going over Mt Hakone led to the 1918 construction of the 7804-m Tanna Tunnel at the 'neck' of the Izu Peninsula. Construction also started in 1922 on the 9702-m Shimizu tunnel, passing under the approximately 2000-m high Mikuni mountain range and shortening the route between Takasaki and Niigata.

These long tunnels could be constructed thanks to advances in construction technologies (such as switching from the Japanese excavation method where a top heading is advanced first to the New Austrian Method where a bottom heading is advanced first). The spread of electric railways also helped because electric trains eliminated the need to ventilate smoke from steam locomotives. Building long tunnels also changed design considerations in selecting routes, marking a departure from the old concept

Figure 1 Ikoma Tunnel Excavation Cress Sections (1914)



(Tokyo Institute of Technology)

of climbing with steep grades and sharp curves and building tunnels only when absolutely necessary.

An important controversy arose in tunnelling technology at this time: the issue of whether to build two parallel single-track tunnels or one double-track tunnel when constructing double-track lines. Most railway tunnels up to that time were single-track, and a new adjacent parallel single-track tunnel was excavated when doubling track. With more opportunities to construct double-track tunnels in this era, opinion was split on which design was best. With parallel single-track tunnels, the excavated cross section is smaller so excavation speed is faster and a more stable tunnel face is secured when digging in weak ground. However, this design is not ideal for ventilating smoke from steam locomotives and overall construction costs tended to be higher.

For this reason, although the Shin-Osakayama and Higashiyama tunnels between Otsu and Kyoto and 2457-m Izumigoe Tunnel between Kozu and Atami on the Tokaido main line were constructed as parallel single-track tunnels, most of the tunnels between Kozu and Numazu, including the Tanna Tunnel, used a double-track cross section.

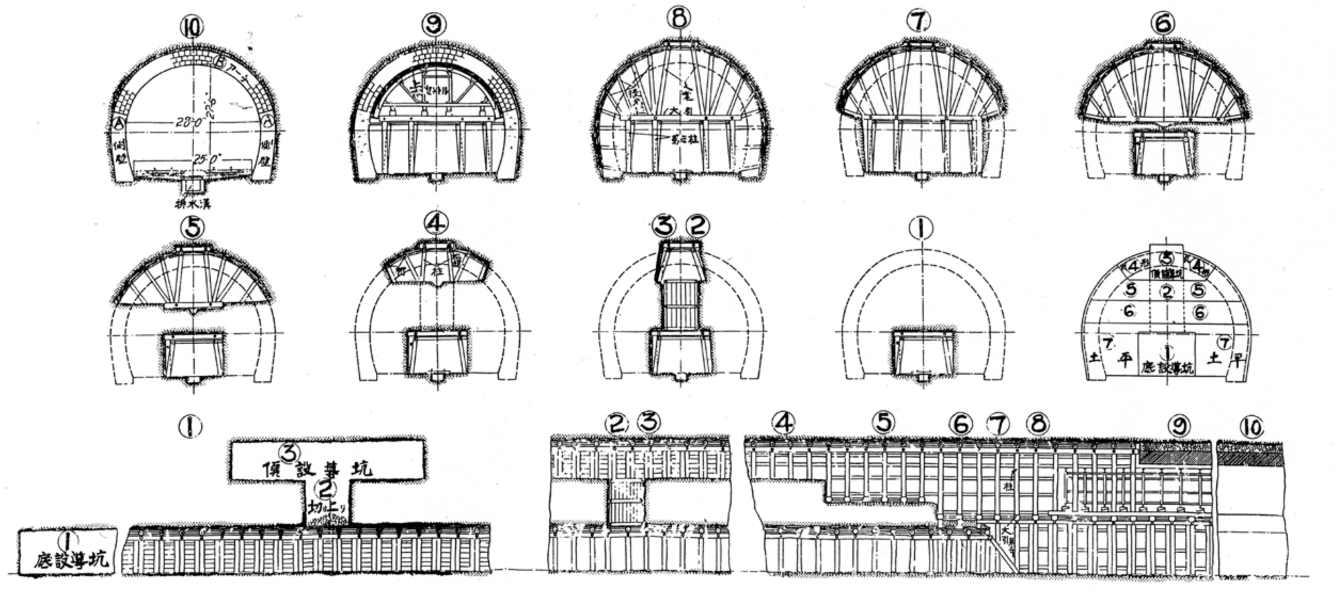
The turning point was the Ikoma Tunnel (Fig. 1) on Osaka Electric Railroad (Kintetsu Corporation today). Construction on this tunnel between Osaka and Nara started in 1911 and its 3388-m length was second only to the Sasago Tunnel. It is a double-track tunnel using standard gauge and was completed in 1914 despite a collapse and flooding, proving that long double-track tunnels could be constructed.

Meanwhile, the New Austrian Method was being introduced from Europe as a replacement to the prevalent top-heading (Japanese) method. It enabled efficient construction of long tunnels in shorter times. With the switch from brick and stone linings to concrete, most tunnels starting from the 1252-m Nokogiriyama Tunnel on the Boso West Line in 1915 embraced cast-in-place concrete and concrete blocks as lining, and most tunnel linings were concrete by the 1920s.

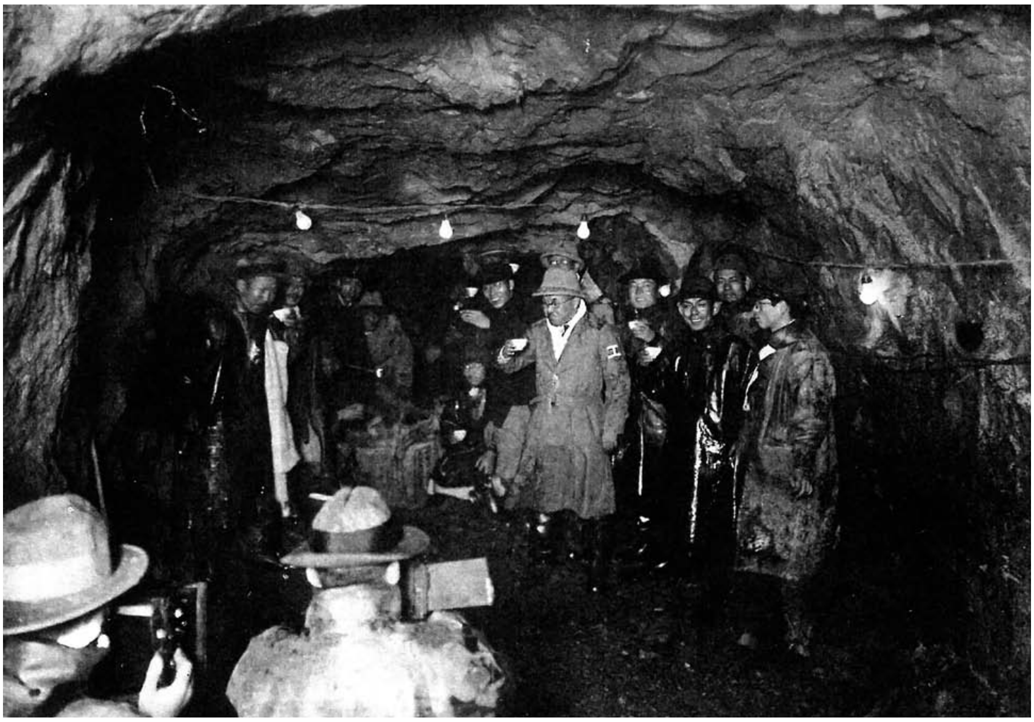
Attempts at difficult construction (1920s to 1930s)

Work on the Tanna Tunnel (Fig. 2), a Japanese tunnel project that became world famous, started in 1918 to improve the steep route over Mt Hakone. The construction was hindered by weak geology with spring water, a large fault fracture zone, and altered rock exhibiting swelling;

Figure 2 Tanna Tunnel Excavation Cross Sections (1934)



(RTRI)



Shimizu Tunnel breakthrough (1929) (celebrated with rice wine and completed in 1931) (RTRI)

it required 16 years to complete and took the lives of 67 workers. Supplementary construction methods such as drainage boring, drainage and detour drift drilling, shield tunnelling, and pneumatic tunnelling were adopted and the experience was applied to later tunnel construction. Robert Ridgway, the Chief Engineer for the New York subway visited the Tanna Tunnel construction site when he was in Japan to attend the World Engineering Congress in Tokyo in 1930, and said that he knew of no other more difficult tunnel to build and expressed his respect for the bravery of Japan's tunnel workers. He also expressed criticism, saying that the difficulty was a result of the engineers failing to conduct geological surveys.

Furthermore, the 1922 construction of the Shimizu Tunnel on the Joetsu Line experienced rock burst due to the high ground pressure caused by more than 1000 m of overhead burden and construction was plagued by large volumes of spring water. Emphasis was placed on mechanized work to excavate the hard bedrock and equipment imported from the USA was introduced to complete the tunnelling in 1929.

Due to the experience of these difficult constructions, engineers grew more interested in geological surveys and their results, so the Ministry of Railways Geotechnical Committee was established in 1930. The Committee, along with outside experts, researched geological surveying methods and soil-testing methods. It prompted systemization of engineering geology, bordering civil engineering and geology and playing a pioneering role in the field.

Other advances included use of reinforced concrete linings to handle expansive ground pressure in the 2919-m Usami Tunnel on the Ito Line completed in 1933; use of small drill jumbos in the 5361-m Senzan Tunnel on the Senzan Line completed in 1934; and adoption of wooden-prop shoring and blasting with electric delay caps in the 3125-m Manaitayama Tunnel on the Oito Line completed in 1936.

In the 1930s, subways were constructed in urban areas using the cut-and-cover method, with mountain tunnelling used on some sections of Tokyo Underground Railway (today's Tokyo Metro) opened in 1927, and Keisei Electric Railway's underground line opened in 1933.

Tunnels during WWII (1930s to 1940s)

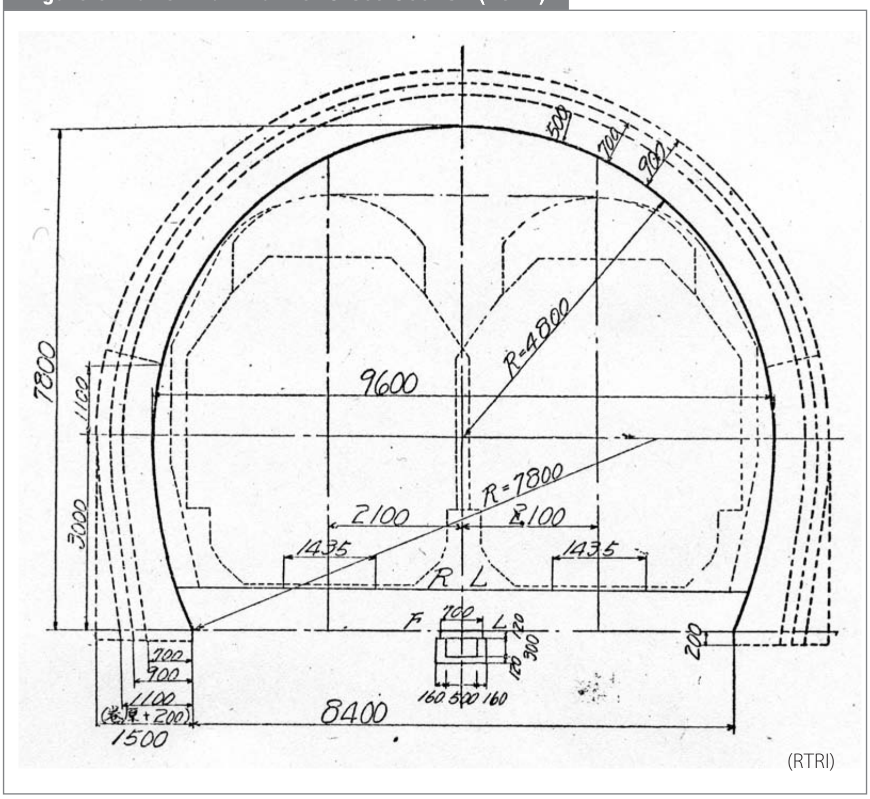
The world's first undersea tunnel was planned for the Kanmon Strait between Honshu and Kyushu, and all Japan's abilities in tunnelling technology were brought together for the project. The idea of a railway link between Honshu and Kyushu was proposed first in 1896 with comparison of bridge and tunnel proposals. The decision to dig an undersea tunnel was taken from the defence perspective. The Kanmon Tunnel was to be built for more than just hauling coal and other ores extracted in Kyushu to industrial areas on Honshu. It was also important as a supply route to expand Japan's might as the military advanced into mainland Asia. Geological surveys such as boring surveys at sea were performed from 1919 onwards.

Construction used mountain tunnelling on the Honshu side and caisson and shield tunnelling on the Kyushu side. The Kanmon Tunnel was the first example of using shield tunnelling in earnest, and extensive preparations were made, such as dispatching engineers to New York to survey riverbed tunnels on the Hudson River. Other techniques were pneumatic tunnelling and cement grouting, and efforts were made to shorten the construction period by confirming the geology by advancing test headers and increasing the number of tunnel faces. Construction started in 1936 with excavation of vertical shafts, and work continued at a rushed pace in the difficult times under a war footing. The down-line tunnel (3614 m) was completed in 1942 followed by the up-line tunnel (3605 m) in 1944.

Construction started on various other tunnels including the Tanna Tunnel in 1942 (Fig 3) for the so-called 'Bullet Train' project with the goal of running high-speed trains on standard gauge. Work, such as geological surveys, went forward on a plan to build a railway tunnel under the Korea Straight, but all these projects were suspended as the war intensified. The tunnel cross section and other design standards along with route plans for the Bullet Train were reflected in post-war shinkansen plans.

Due to wartime shortages, tunnel designs in this period saved materials by means such as omitting concrete linings, substituting stone once again for concrete linings, and leaving the bedrock exposed. Also, many engineers involved in tunnel construction were moved to construction of underground air-raid shelters, bunkers, bases, and munitions factories until the war's end in 1945.

Figure 3 Bullet Train Tunnel Cross Section (1942)



(RTRI)

Post-war restart (1950s to 1960s)

Construction of new tunnels was suspended for a time after the war but an unofficial committee was formed in

Tokaido Shinkansen Shin-Tanna Tunnel (1964) (parallel to conventional-line Tanna Tunnel on north side) (RTRI)

1946 to study a railway link under the Tsugaru Strait between Honshu and Hokkaido and surveying started for an undersea tunnel—today's Seikan Tunnel.

The first post-war tunnel was the 5063-m Ohara Tunnel on the Iida Line, built to relocate the line away from a section being flooded by construction of the Sakuma Dam. Construction of the Sakuma Dam was hastened to make-up post-war electricity shortages, so the Ohara Tunnel also had to be constructed quickly. The latest tunnelling machinery was imported from the USA and construction was completed in 1957, 2 years after the start. Full-face excavation was used for the Ohara Tunnel, with equipment such as drill jumbos, mobile lining frames (steel forms), and electric muck loaders. To secure a wider work space, steel supports were introduced as an alternative to general-purpose wooden-prop shoring. Steel supports were embedded in the concrete lining and not removed, eliminating the dangerous work of removing wooden-prop shoring, and making work more efficient and safer. Steel supports came into common use with the opportunity provided by this construction project. Installation of concrete lining, which had been done manually until this time, was made more efficient and less labour intensive using steel forms and concrete pumps.

The huge shortage in transport capacity during the post-war reconstruction required intensive construction to lower steep grades and increase track capacity (by double tracking). The track improvements between Tsuruga and Imajo on the Hokuriku Line including the 13,780-m Hokuriku Tunnel used work drifts such as inclined and vertical shafts to cut construction time. Steel supports secured wider work spaces and new construction methods, such as double-track, full-face tunnelling were attempted; the bottom heading method was adopted as the standard excavation method matching Japan's complex geology. The Hokuriku Tunnel took 4.5 years to build and was completed in 1962. Tunnelling technologies for long double-track tunnels established by construction of the Hokuriku Tunnel were adopted later for shinkansen tunnels.

From shinkansen tunnels to Seikan Tunnel (1970s to 1980s)

The Tokaido Shinkansen opened in 1964 with straight tracks, gradual grades, and gentle curves supporting high-speed operations in excess of 200 km/h. Approximately 13% (68.5 km) of the 515 km between Tokyo and Shin-Osaka was in tunnel. This compares to the 5% (27 km) of the 556-km Tokaido main line running almost parallel. The 17-year planned construction period for the 7959-m Shin-Tanna Tunnel, the longest tunnel on the Tokaido Shinkansen, reflected expected construction difficulties, but it was completed in 5.5 years, demonstrating advances in Japan's tunnelling technologies at that time.

Tunnels tended to be much longer on the San'yo

Seikan Tunnel Breakthrough (1983) (opened in 1988 as world's longest tunnel)
(Japan Railway Construction, Transport and Technology Agency (JRTT))

Shinkansen built after the Tokaido Shinkansen, focusing interest on faster construction methods, especially tunnel boring machines (TBM) entering commercial use in Europe. A Swiss TBM with a cutting diameter of 3.6 m was used to excavate the survey shaft for the Seikan Tunnel in 1966. This was followed by a domestically built TBM licensed from overseas; it had a cutting-head diameter of 2.3 m and was used to bore the bottom heading of the 1570-m Kinoura Tunnel on the Hokuriku Line in 1967. Based on these tests, domestic TBMs with a cutting diameter of 4.5 m and a 'Big John' boom-type full-face excavation machine imported from the USA were used to excavate tunnels on the San'yo Shinkansen from 1968. However, Japan's complex geology proved difficult and use of TBMs and full-face excavation machines for railway tunnels was halted after trials on a few tunnels.

Partial-face excavation machines were used for the 798-m Shiroyama Tunnel on the Kagoshima Line in 1969, and became popular as excavation machines with broad application to complex geology. Their use was expanded after introduction of the New Austrian Tunnelling Method (NATM) covered later. These partial-face excavation machines were improved road-headers introduced by the USSR in 1961 for mining, and caught on in tunnel construction.

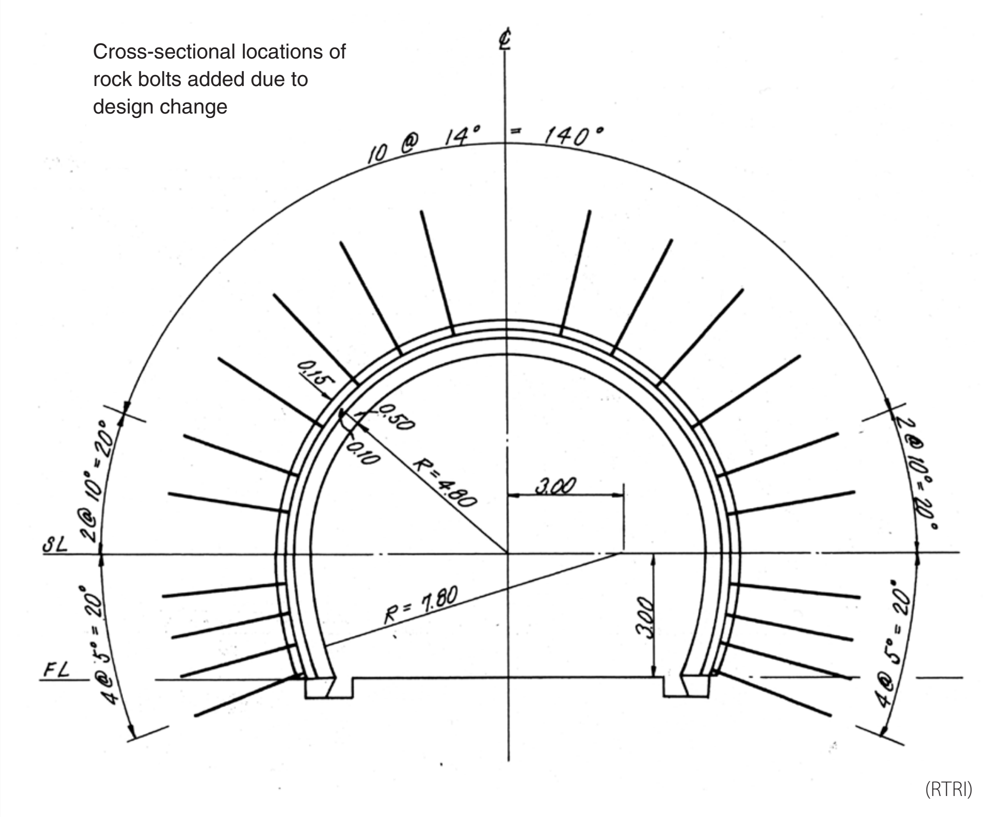
Steel supports introduced with the Ohara Tunnel construction were the main supports, but trials using rock bolts from mining were conducted in the 2534-m Okamizaka Tunnel and the 2933-m Sone Tunnel in 1956. After a long period of non-use, they were finally used to cut the cost of constructing the 10,700-m Saisho Tunnel, 5305-m Takehara Tunnel, and 18,713-m Shinkanmon Tunnel on the San'yo Shinkansen in 1972.

Shotcrete was also used to prevent ground loosening during the 1967 construction of the 2640-m Shintokawa Tunnel on the Momijiyama Line (later Sekisho Line) and the 53,800-m undersea Seikan Tunnel started with a survey shaft in 1964 and now the world's longest railway tunnel. Boring of the Seikan Tunnel main shaft started in 1972, followed by the pilot tunnel breakthrough in 1983, and start of railway operations in 1988. New techniques were developed, including pilot boring to characterize the geology ahead of the cutting face, chemical grouting to improve the ground around the tunnel and stop water ingress, and shotcreting to control ground loosening at the early stage. Committees such as one to investigate technologies for the Seikan Tunnel (1967 to 1985) and one on earth pressure on the lining of the Seikan Tunnel (1971 to 1981) were established to support construction work.

NATM Introduction

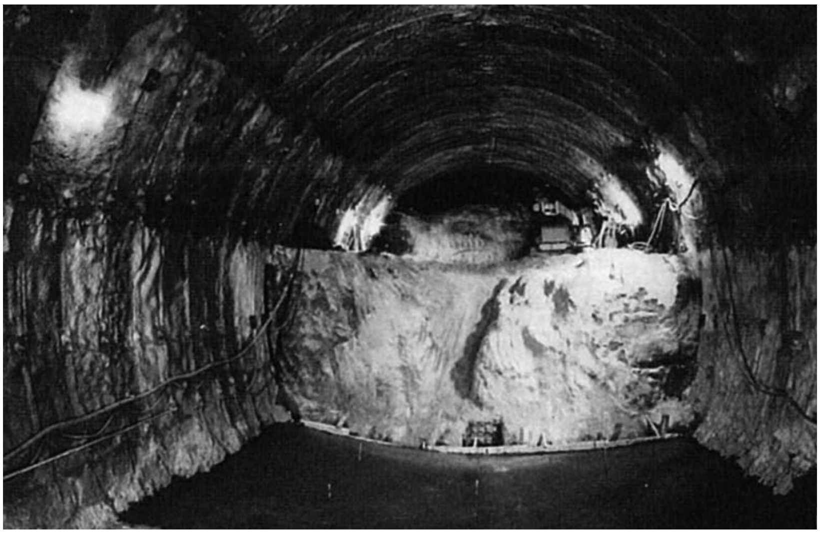
NATM, the standard method for mountain tunnelling today, was developed by Austria's Ladislaus von Rabcewicz in

Figure 4 NATM on Nakayama Tunnel (1976)



1964. It features supports consisting mainly of rock bolts and shotcrete, and construction is performed according to ground conditions thanks to measurement control.

NATM was first introduced in Japan by Yukitoshi Oka of Kyoto University in 1974, and representatives of the Japan Tunnelling Association participating in the International Tunnelling And Underground Space Association (ITA) general assembly in Munich in 1975 observed NATM construction sites in Switzerland and Austria. Against this background, Japanese National Railways (JNR) and the Japan Railway Construction Public Corporation (JRCC) were motivated to try NATM and it was used in 1976 on a trial basis by JRCC on a section with squeezing in the 14,857-m Nakayama Tunnel (Fig. 5) on the Joetsu Shinkansen. JNR selected four tunnels including the 255-m No. 1 Hiraishi Tunnel on the Tohoku Shinkansen in 1978 as test NATM construction sites, and difficult conditions of decomposed granitic soil with little overburden were overcome to complete the construction.



NATM on No. 1 Awazu Tunnel (1978)
(foreign engineers like Leopold Müller were brought in for early advice) (RTRI)

The combinations of NATM support materials can be changed easily to match geological conditions, so NATM caught on quickly as a tunnelling method with adaptability to Japan's complex geology. NATM was used in all tunnels built by JNR from 1979 and a proposal for design and construction guidelines was established in 1982, positioning NATM as the standard mountain tunnelling method for railways.

Experts from other countries were invited to provide technical instruction when NATM was introduced, with Austrian Professor Leopold Müller from Karlsruhe Institute of Technology in Germany invited to the construction site for the No. 1 Hiraishi Tunnel on the Tohoku Shinkansen in

1978. Professor Müller also provided technical instruction for the 245-m No. 2 Hiraishi Tunnel and the 190-m No. 1 Awazu Tunnel.

Along with introduction of NATM, the Finite Element Method (FEM) and other design methods using numerical analysis were developed and came into common use thanks to the greater processing capacity and speed of computers. With introduction of NATM, construction management technologies using measuring instruments such as inner space displacement gauges, underground displacement meters, and earth pressure gauges advanced, and logical approaches were taken based on rock dynamics.

A flexible response to complex geology was possible using flexible tunnel design based on results from measuring instruments and computer analysis, creating a revolution in tunnel construction when combined with designs based on rock type.

Backed by these advances in NATM and peripheral technologies, reliable construction methods for sedimentary ground were modified with supplementary construction methods such as quick construction of hard rock ground and soil stabilization. In a 377-m section of the 2100-m Narita Airport Tunnel completed in 1979 for the (now abandoned) Narita Shinkansen, sand diluvium with an earth cover of less than 10 m was excavated over a large cross section of 145 m^2, and ground surface subsidence was successfully held to a much lower level than earlier construction methods. NATM was also used for urban tunnels where shield tunnelling was mainly used, such as the Negishi Tunnel on Yokohama Municipal Subway Line 3 completed in 1980 and Mitsuzawashimocho and Mitsuzawakamicho stations with large cross sections of 146 m^2. Its ability to cut construction costs plus easy adaptability to large cross sections led to increasing adoption.

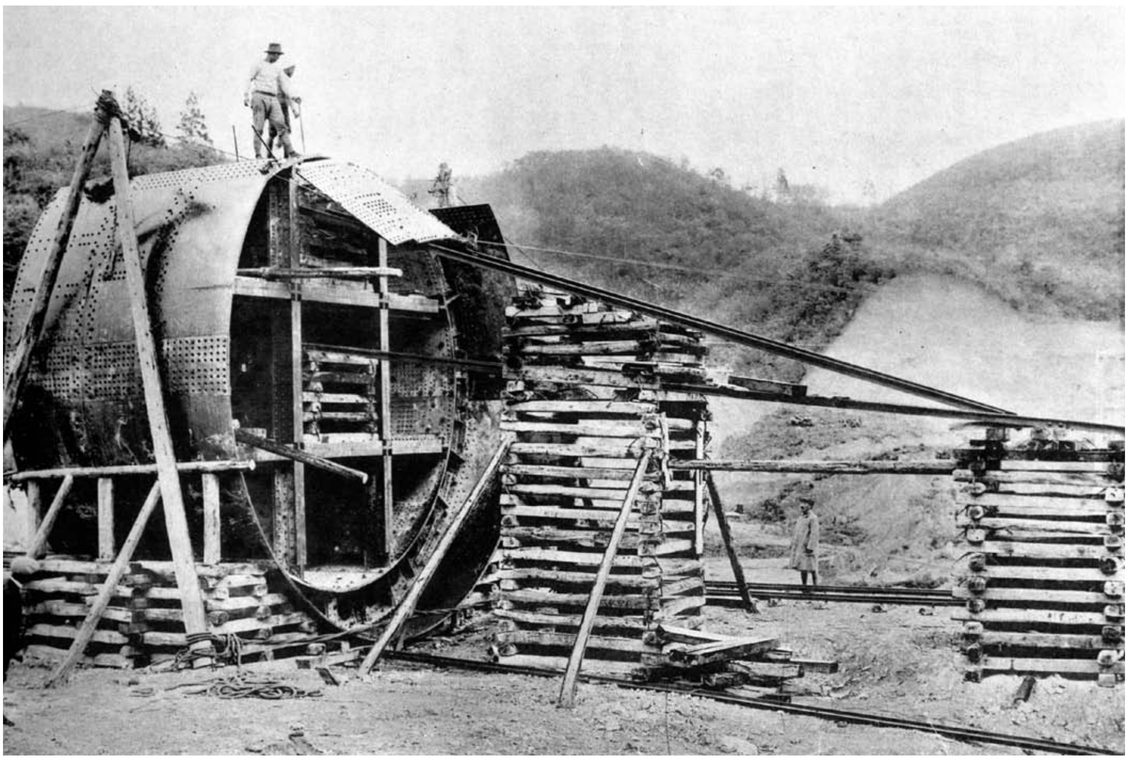
The application of NATM to urban tunnels grew due to its small impact at the ground surface and NATM was used for the large-cross-section, 72-m section at the east tunnel approach of the Keiyo Line to Tokyo Station completed in 1990.

Cross Diaphragm (CRD) split construction work was undertaken to minimize ground surface subsidence at the 2367-m Narashinodai Tunnel on the Toyo Rapid Railway Line with a large 153-m^2 cross section completed in 1996.

A general jumbo was developed to perform shotcreting, steel-support assembly, and rock-bolt placement with one vehicle for the 25,808-m Iwate Ichinohe Tunnel on the Tohoku Shinkansen. Such high-level tunnelling mechanization combining construction machinery with ITC technologies was systemized as a Tunnel Work Station (TWS) used in construction of the 1737-m Yokokabe Tunnel on the Agatsuma Line and elsewhere.

History of Shield Tunnelling

Shield tunnelling was first used by Sir Marc Isambard Brunel (1769–1849) in the UK on the Thames Tunnel under the

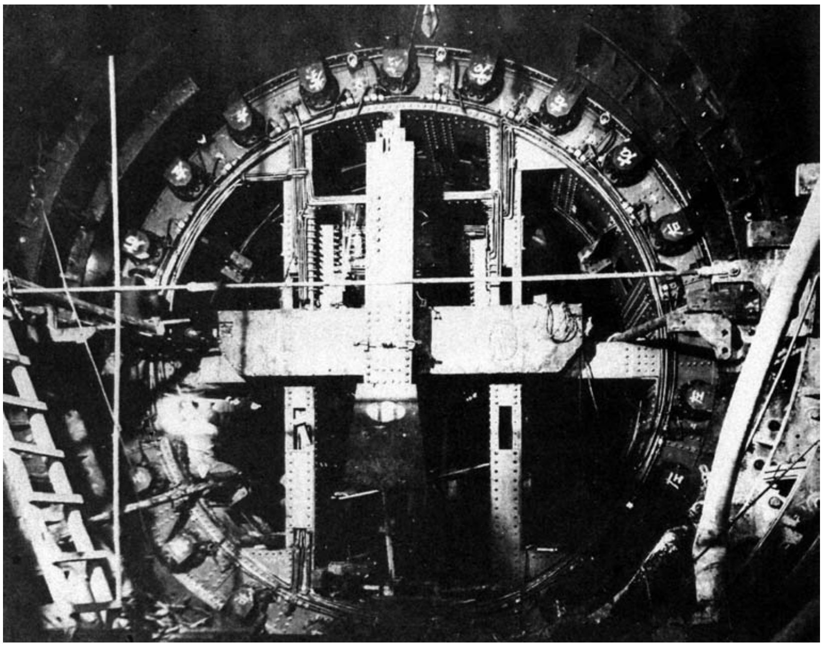


Oriwatari Tunnel shield machine (1920) (Japan's first shield tunnel)

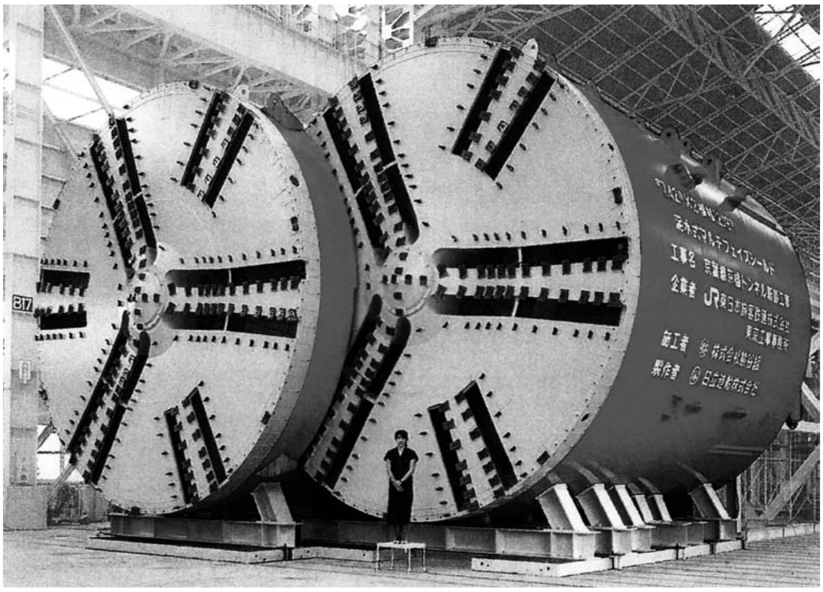
River Thames in London and was patented in 1825. The first tunnel in Japan built using shield tunnelling was the 1438-m Oriwatari Tunnel on the Uetsu Line where a 7.4-m diameter Japanese-built shield machine was used to breakthrough a section with squeezing in 1920. However, the shield machine proved difficult to control and only 184 m was excavated using it. Shield tunnelling was also used for work shafts on the Tanna Tunnel and in construction of the Kanmon Tunnel (7.2-m diameter) but these are the only three pre-war examples of railway tunnels using shield tunnelling.

It was a long time before shield tunnelling was used again for the arch of the Nagatacho No. 2 section on the Eidan Marunouchi Subway in 1957. This was followed in 1960 by construction of a single-track parallel, circular shield tunnel in the Kakuozan construction section of the Nagoya Municipal Subway Higashiyama Line. As a result, shield tunnelling gained a reputation as a safe method for excavating urban tunnels and became popular centred on subway construction.

The first shield machines all used manual digging, but a single-track cross-section mechanical shield machine was introduced in 1964 for the Tanimachi construction section of the Osaka Municipal Subway Tanimachi Line. Manual-digging, double-track cross-section shield machines entered practical use in 1965 for the Hoenzaka construction section of the Osaka Municipal Subway Chuo Line; mechanical, double-track cross-section, shield machines were used in 1968 for construction on Kinki Nippon Railway between Uehonmachi and Namba.



Kanmon Tunnel excavated using 7.2-m diameter shield machine (1942)
(Japan Society of Civil Engineers (JSCE))

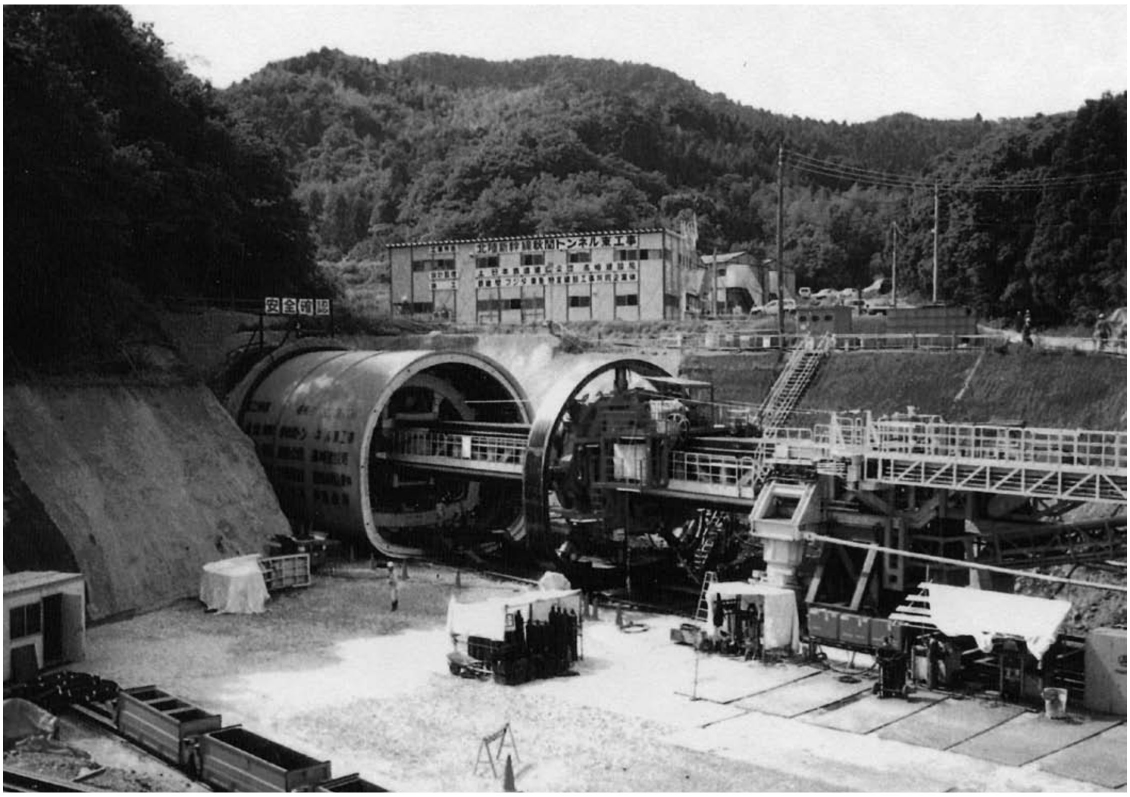


MF shield machine (1998) (double-O-tube shield machine developed to construct double-track tunnels with smaller cross section) (JR East)

Open-type shields used pneumatic tunnelling as well, but problems such as oxygen-starvation accidents and ground subsidence occurred, so original Japanese technologies were developed for slurry shields and earth-pressure shields. Single-track cross-section slurry shields were used for the first time in 1970 for the undersea part of the Haneda Tunnel on the Keiyo Line. A 12.7-m double-track cross-section semi-mechanical large bore shield machine was used for advancing a pilot shield for soil stabilization in the Kaneijibashi and Shitaya construction sections of the Tohoku Shinkansen completed in 1985 and for the extension line to Tokyo Station on the Tohoku Shinkansen completed in 1991. An OD12.6-m, double-track cross-section semi-mechanical large bore shield machine was used for the 1133-m No. 1 Ueno Tunnel.

Shield-tunnel construction is more stable for parallel single-track cross-section tunnels than for double-track cross-section tunnels, but requires acquisition of more land. Multi-face (MF) shields with two linked circular-section boring machines were developed in 1988, and used to excavate a 623-m section in the Kyobashi Tunnel on the Keiyo Line.

To reduce shield-tunnelling costs and improve construction efficiency, the Extruded Concrete Lining


ECL on Akima Tunnel (1990) (developed to apply shield tunnelling technology to mountain tunnelling) (JRTT)

(ECL) method was developed for mountain tunnelling too. ECL was first used for a head-race tunnel at JR East's Shinano River hydroelectric power plant in 1987, and was applied later in 1990 to the 8310-m Akima Tunnel on the Hokuriku Shinkansen. Furthermore, the Shield machine/ Extruded concrete lining/NATM/System (SENS) combining the benefits of shield machines, ECL, and NATM, was developed and used on the 4280-m Sanbongihara Tunnel completed in 2010.

History of Cut-and-cover Tunnelling

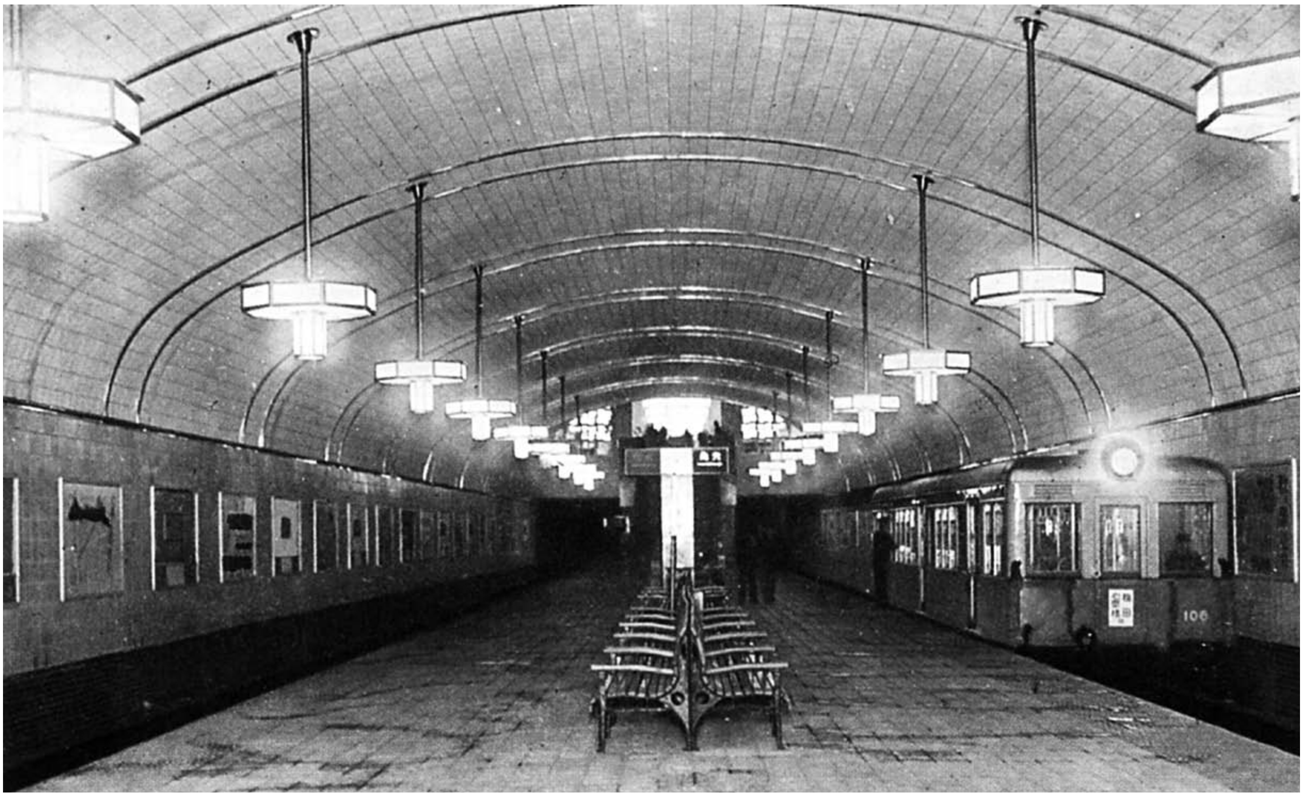
The first cut-and-cover tunnel in Japan was the Ishiyagawa Tunnel mentioned previously. It was built directly under a raised river bed and completed in 1874. Cut-and-cover tunnelling was later used frequently for raised river-bed tunnels and tunnels in hilly areas with shallow overburden, but was used most widely for subway tunnels.

Japan's first subway was the Tokyo Underground Railway opened in 1927. Chief Engineer for the Berlin Subway, Rudolf Briske, was brought in to give instruction in the construction. In cut-and-cover tunnel construction, I-beams are used for soldier piles and soil is retained by wooden lagging while excavating. In the parts with roads or tracks, I-beams are installed as cross beams and the road face is lined with timber. The tunnel itself generally had a reinforced-concrete box-frame structure between stations with a steel-framed reinforced-concrete structure at stations.

The Osaka Municipal Railway opened in 1933 used a special construction method while the country was on a war footing. Soil retention steel pilings were used directly as part of the wall frame and enclosed in concrete. Subway stations used reinforced-concrete arch structures to secure large spaces without columns, and unreinforced-concrete arch cross-section tunnel construction was also used to save steel. Cut-and-cover tunnels with steel-frame or reinforced-concrete frame structures were also built. These include the Kyoto Underground Line of Shinkeihan Railway (now Hankyu Kyoto Line) opened in 1931, and the Ueno Underground Line of Keisei Electric Railway opened in 1933.

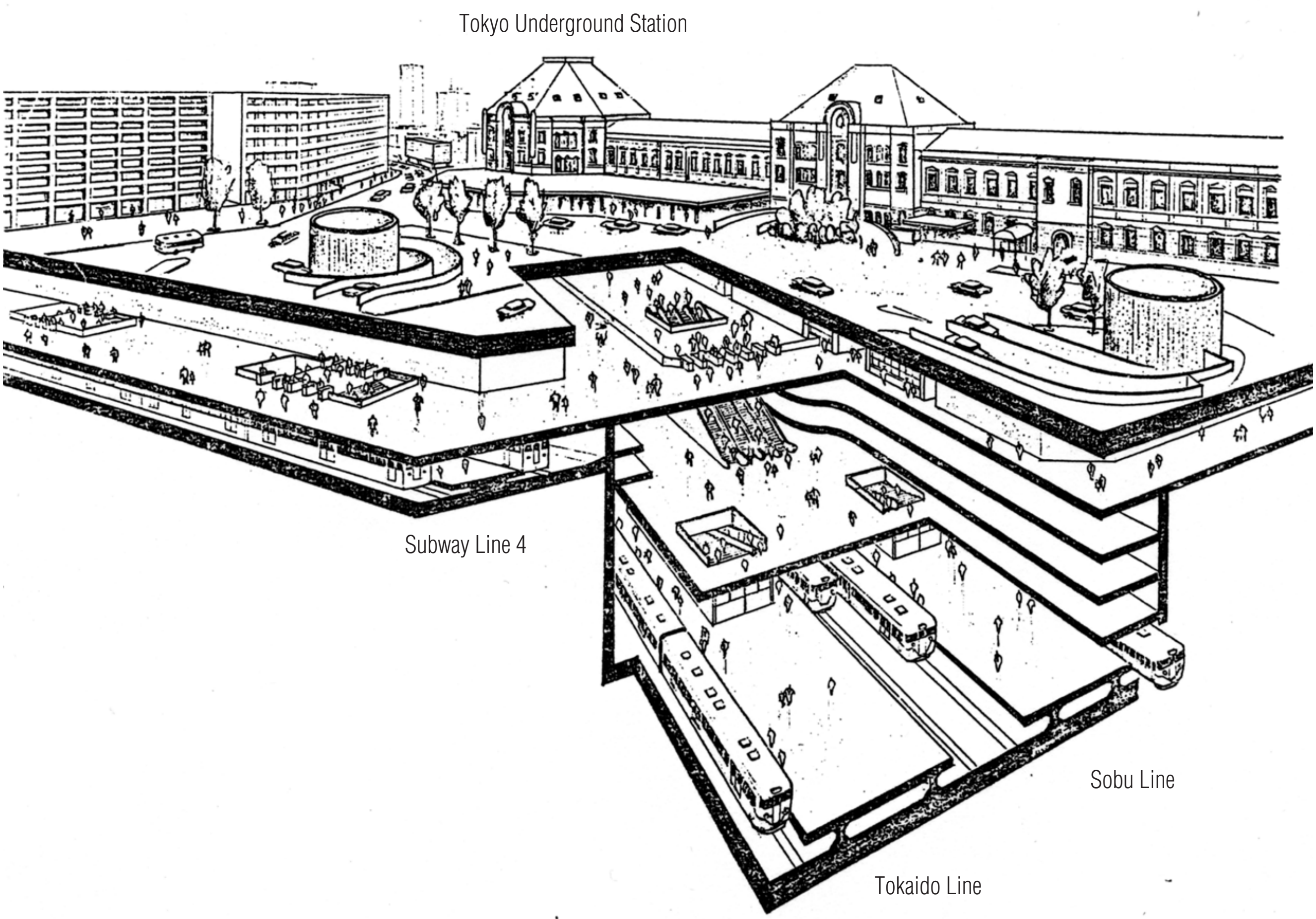
Tokyo Metro's Marunouchi Line constructed soon after the war was built mainly using cut-and-cover tunnelling with concrete or cast-iron road-bed lining plates. While soldier piles with wooden lagging were common, the Italian ICOS method was introduced for cut-and-cover tunnelling near Honancho on the Marunouchi Line in 1961, making it an early example of underground continuous-wall construction.

Soil retaining using soldier piles and wooden lagging continued to be the main method, but boring with earth drills and erecting became more common for driving piles than striking with hammers, greatly reducing construction noise. Large work spaces were secured with greater safety



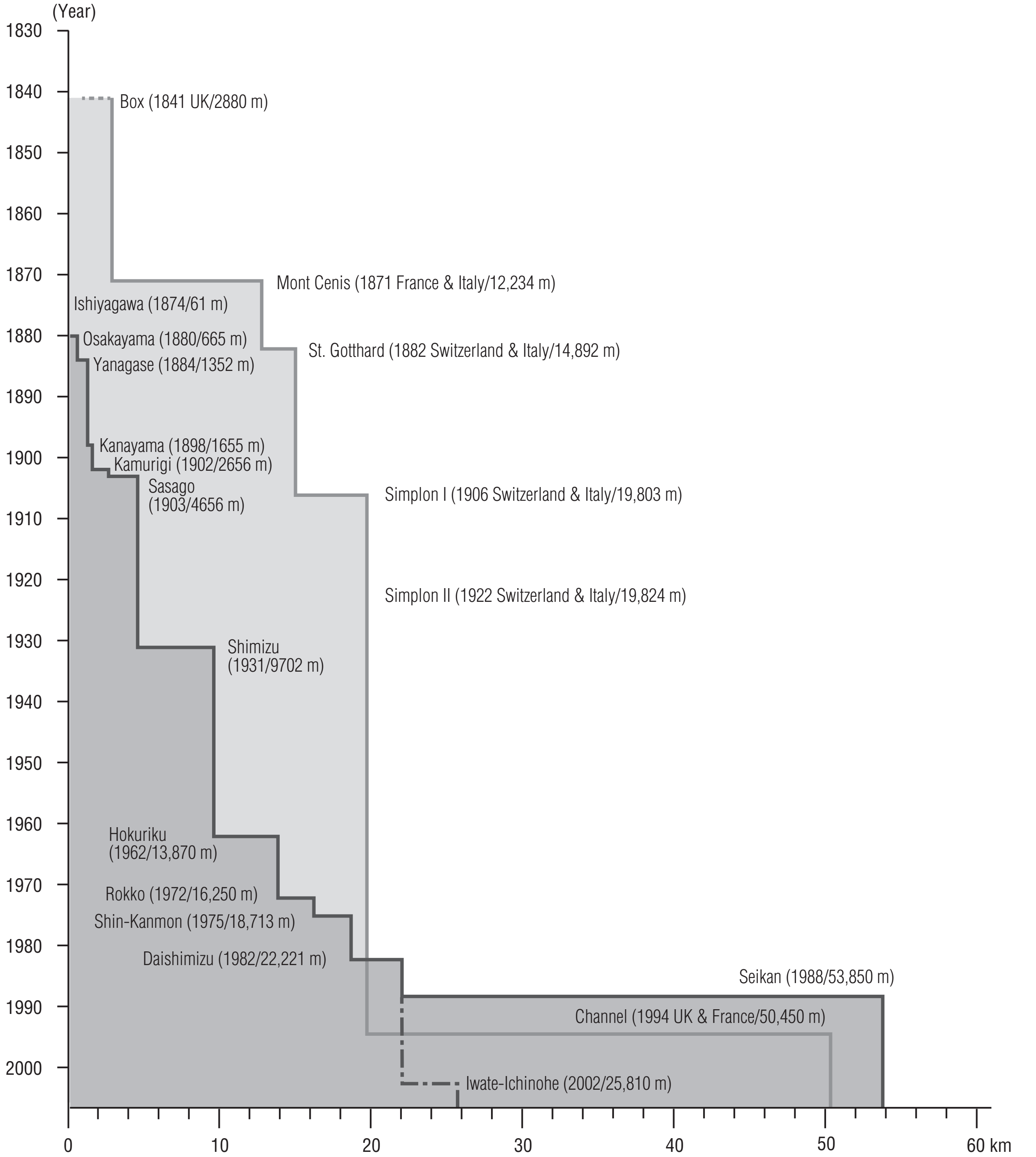
Station on Osaka Municipal Railway Midosuji Line (1933) (large cross-section subway station without columns) (Author)

Figure 5 Tokyo Underground Station Built by Cut-and-Cover Tunnelling (1972)



(JNR)

Figure 6 History of World's Longest Railway Tunnels (Excluding Subway Tunnels)



(Author)

by changing from wooden-prop shoring to steel supports making frequent use of H-beams. Furthermore, boring could be done safer and deeper under urban areas with existing complex underground structures by using the well-point, trench cut, and underpinning methods.

As shield tunnelling became more common for subway construction, cut-and-cover tunnelling was used to build the work bases from which shield machines advanced.

The underground part of Tokyo Station for through services between the Tokaido and Sobu lines (construction started in 1968, partially opened in 1972, and completed in 1975) has a rigid-frame structure with steel-frame reinforced concrete five stories underground (Fig. 5). It is a large underground station with a maximum width of 43.2 m and height of 24.4 m, and has two island platforms serving the 15-car EMUs. The same construction technologies were used later for the underground parts of Ueno Station (completed in 1985) for the Tohoku Shinkansen.

History of Immersed-Tube Tunnelling

Immersed-tube tunnelling is used for underwater tunnels; sections are first prefabricated onshore, floated to the construction site, submerged, and connected to complete the tunnel. This method was first used in 1893 to construct a sewer under Boston Harbor in the USA. In Japan, it was first applied to a river-bed tunnel under the Aji River in Osaka in 1935.

The first immersed tube railway tunnel in Japan was a 480-m section of the Haneda Tunnel on the Tokyo Monorail completed in 1964. The method was used again for tunnels such as the Haneda Tunnel on the Keiyo Line completed in 1969 (Tama River section: 48 m/Keihin Canal section: 33 m), and the Dojimagawa Tunnel (72-m section) and Dotonborigawa Tunnel (25-m section) of Osaka Municipal Subway, also completed in 1969. There are few examples of this special construction method.

Conclusion

Railway tunnels in Japan started with the 61-m Ishiyagawa Tunnel built in 1870 under the instruction of a British engineer. At around the same time, the 12,234-m Mont Cenis Tunnel (Fig. 6) was completed in the European Alps in 1871 and the almost 15,000-m St. Gotthard Tunnel was under construction (completed in 1882), demonstrating an unmistakable gap in the technology level between the West and Japan. Combining mining and stonemason techniques from the Edo Period with western technology allowed Japan to develop domestic technologies relatively quickly and wean itself from reliance on foreign tunnelling engineers.

Japan's complex topography and geology proved a major obstacle to tunnel construction, and difficult construction was faced from the 1920s such as the Tanna Tunnel and Shimizu Tunnel. Improvements in excavation techniques, application of geological surveying, introduction of mechanized construction, and the like, were made and new technologies were introduced drawing lessons from overseas tunnel construction. The world's first undersea Kanmon Tunnel was completed as a result in 1932.

Post-war tunnel construction underwent a major change with geological surveying and mechanized construction coming into common use and a switch from wooden-prop shoring to steel supports. New construction methods for shinkansen tunnels allowed longer tunnels to be completed quickly. Furthermore, NATM introduced in the late 1970s caught on as a construction method matching Japan's geology.

Japan's tunnelling technologies have matured to a point where they are highly regarded worldwide, but we should not forget the efforts of earlier tunnelling engineers. ■

Further Reading

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