Geotechnical Aspects of Underground Construction in Soft Ground – Negro & Cecilio Jr. (Eds)
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Amazing underground construction technology in Japan

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ABSTRACT: This second Fujita lecture covers the current underground construction in Japan, which amazes the international underground construction engineers with opening their eyes. The six amazing case histories are introduced with the large-size and novel underground construction technologies used in these case records and the planning. The Metropolitan Area Outer Discharge Channel tunnel (MAODC) featured by the large underground shrine cavern, the metropolitan expressway and the Gaikan projects including large diameter Shied TBM tunnelling and large size open excavation, the Maglev bullet train Shinkansen, the new connecting train network system and the refurbishment of Tokyo metro train station are introduced.

1 INTRODUCTION

The Fujita lecture is one of the honor lectures of ISSMGE, which memorizes the late Professor Keiichi Fujita, who is the founder and the first chair of TC28 (currently TC204). The first Fujita lecture was given by Prof. Hugh D. St John at IS-Seoul 2014 on the Urban development: Decision making processes in the planning of sub-structure construction in London.

The second Fujita lecture covers the current underground construction particularly within the eastern Japan, which amazes the international underground construction engineers with opening their eyes. The six amazing case histories are introduced with the large-size and novel underground construction technologies used in these case records and the planning. The Metropolitan Area Outer Discharge Channel tunnel (MAODC) featured by the large underground shrine cavern, the metropolitan expressway and the Gaikan projects including large diameter Shied TBM tunnelling and large size open excavation, the Maglev bullet train Shinkansen system, the new connecting train network system and the renovation of Tokyo metro train station in the soft alluvial deposit are introduced to demonstrate the current underground construction activities in Japan.

2 LARGE UNDERGROUND SHRINE CAVE AND THE MAODC PROJECT

2.1 *Outline of MAODC*

The metropolitan area outer discharge channel tunnel (MAODC) is the first underground river to be constructed in Japan, under the National highway RL 16 at the depth 50 m below the surface. The location of the MAODC is shown in Figure 1 and the transparent bird eye's view of MAODC underground structures are demonstrated in Figure 2.

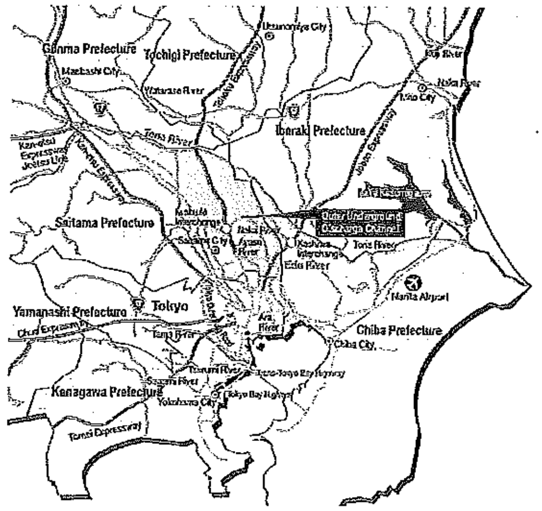


Figure 1. Location of MAODC.

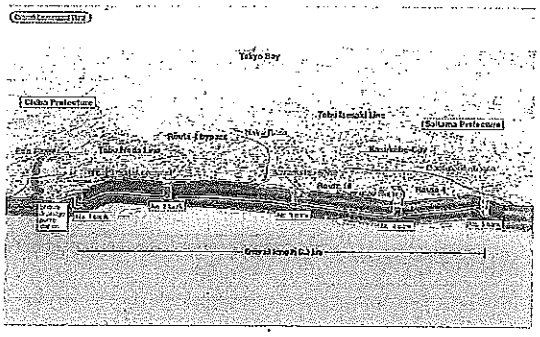


Figure 2. Bird eyes view of MAODC.

The finished tunnel diameter is 10.6 m and the first phase is 6.3 km long. The deep large diameter shaft is created for the launching the TBM machine and the huge water storage space, which is named after the bank. The slurry shield TBM method is used for the channel tunnel excavation, as it is the most reliable for a large diameter tunnel under high water pressure.

Many innovative technologies are used in construction, such as an automated material transportation system, an automatic segment erection system, and information technologies. This chapter presents the special features of MAODC including design, construction, maintenance and the latest tunneling technologies. Construction was started in March 1993 and was completed in June 2006.

That is designed to eliminate flood damages in the middle reach of the Nakagawa river and the Ayasegawa river and provide another residential area for the Metropolitan Tokyo area. It connects the small and medium size rivers in this basin to the Edogawa river and diverts the floodwater to that river.

The Nakagawa/Ayasegawa river basin is a low-level area surrounded by the Edogawa river, the Tonegawa River, and the Arakawa river. As the discharge capacity in this basin is not enough in the event of a heavy rainfall, the wide area is flooded for a long time. This area has recently become heavily urbanized and many houses are damaged in the case of a flood.

A comprehensive flood control project has long been needed in this area and a rapid completion of the project is expected. The effect of MAODC is evaluated by using 1992 flood data, which shows that the flooded area is reduced to one-sixth and the number of people affected by flooding is reduced to one-forty fifth. The total project cost of MAODC is estimated as 240 billion Japanese Yen.

2.2 *AODC system and construction*

The MAODC consists of the channel tunnel, five shafts (or banks), intake structure and the pump station, as is shown in Figure 3. Tables 1 and 2 summarize the specifications of the banks and the tunnels.

When the river water level rises due to a storm, water flows over the crest of the weirs at each intake structure and is flowing through the tunnel and is pumped 200 m³/s to the Edogawa River at the pump station. Since the runoff of the Edogawa River is delayed compared with that of other rivers in this basin, the discharge from MAODC will not adversely affect to the Edogawa River.

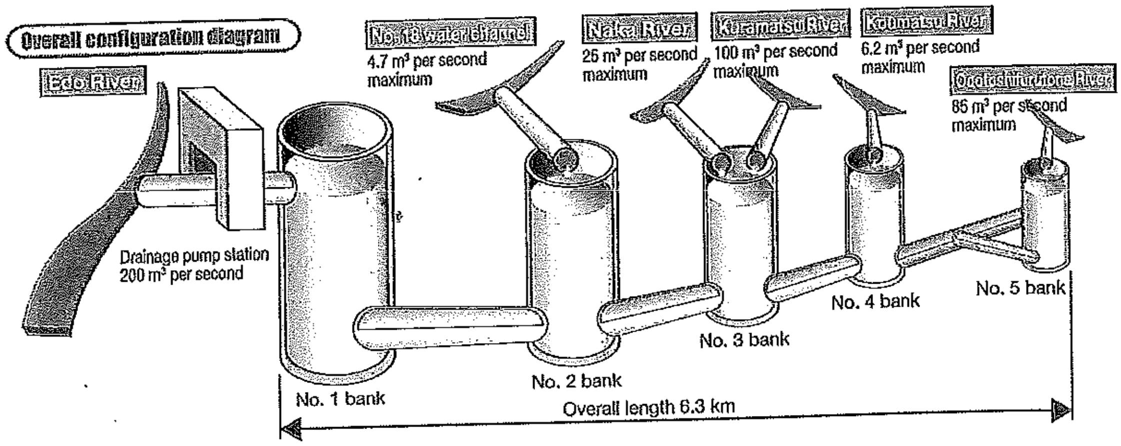


Figure 3. Drainage system of MAODC.

Table 1. Specification of banks.

	Upper side wall	Lower side wall	Bank depth	Construction method
No. 1 bank	Φ31.6 m Wall thickness 2.5 m	Φ30.0 m Wall thickness 3.3 m	GL-72.1 m	Inveted lining method and permanent lining method
No. 2 bank			GL-71.5 m	
No. 3 bank			GL-73.7 m	
No. 4 bank	Φ25.1 m Wall thickness 2.0 m	Φ22.5 m Wall thickness 3.3 m	GL-69.0 m	
No. 5 bank	Φ15.0 m Wall thickness 2.0 m	Φ15.0 m Wall thickness 2.0 m	GL-74.5 m	Super Open Caisson System (SOCS)

Table 2. Specification of tunnels.

Section	Tunneling section	Extension of tunnelling	Inside diameter of tunnel
No. 1 tunnel	From No. 1 bank to No. 2 bank	1,396 m	10.6 m
No. 2 tunnel	From No. 2 bank to No. 3 bank	1,920 m	10.6 m
No. 3 tunnel	From No. 3 bank to No. 4 bank	1,384 m	10.6 m
No. 4 tunnel	From No. 3 bank to Oootoshirfurutone River	1,235 m	10.9 m
Connecting tunnel	From No. 5 bank to No. 4 tunnel	380 m	6.5 m

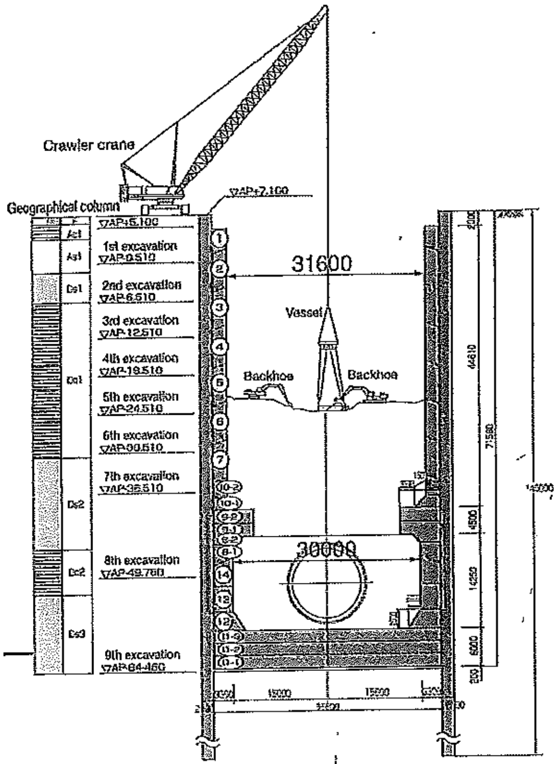


Figure 4. Construction method for the large and deep shafts, i.e. the banks (units in mm).

The five banks from No. 1 to No. 5 are interconnected to each other through the underground tunnel and used for taking in flood water from the rivers. These are gigantic cylindrical facilities. Each of them is approximately 70 m deep and has an inner diameter of approximately 30 m. They are large enough to accommodate a space shuttle or the Statue of Liberty. They are constructed by the inverted lining method and permanent lining method, as shown in Figure 4.

The overburden depth for the structural design is determined as 50 m for the following reasons. The tunnels are located in the stable diluvial ground to facilitate the construction and to minimize the ground disturbance. The maximum ground water pressure is 600 kPa where the shield tunneling methods have been successfully utilized.

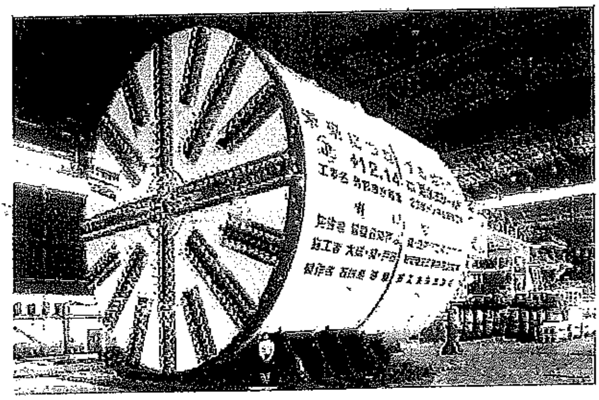
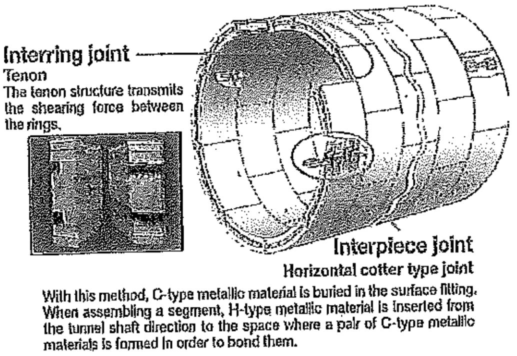


Figure 5. Large diameter shield TBM for tunnels.

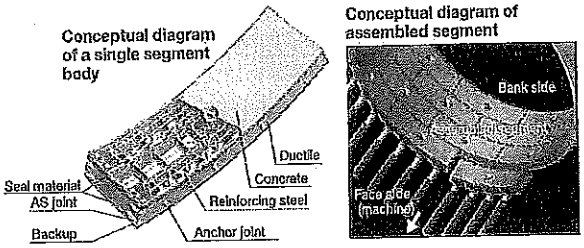
The slurry shield TBM shown in Figure 5 has been employed for the construction since it must have been carried at greater underground depths and a large inner diameter of 10.6 m is required.

The tunnel breakthrough was in 2002 between Tunnel sections No. 1 and No. 2, which starts from Bank No. 1 and ends at Bank No. 3. Subsequently, Tunnel section No. 3 and No. 4, which starts from Bank No. 3 and terminates at the Oootoshi-furu-Tonegawa River broke through in 2004 and the connecting tunnel between Bank No. 5 and Tunnel section No. 4 broke through in 2005.

The MAODC is an internal water pressure tunnel and new technologies have been employed for the construction. A new type of segment lining has been developed using the state of the art technology so that the construction work carried out utilizing them is made easier and so that the intended finish is achieved on time. Figure 6 indicates the new technologies adopted in the shield TBM tunneling.



a) horizontal cotter type RC segment (Section 1 tunnel).



b) DRC segment (Section 4 tunnel).

Figure 6. New technologies used in shield TBM tunneling.

The followings are the technical features used in the shield tunnel construction.

1. Supporting internal water pressure: Not only safe against outer pressure, but also against the internal water pressure.
2. Inner surface smooth: A segment free from concavities resulting from coming in contact with flowing water.
3. High rigidity: Enhancement of bonding force of segments by employing wedge structures for the joint.
4. High-speed automatic assembly: Wedge effect based management of fastening and elimination of supplementary work.

2.3 *Underground shrine cave*

Pressure adjusting water tank is an enormous water cistern built at a position 22 m below the ground surface level to reduce the flow of water and drain it smoothly into the Edogawa River. It is 177 m long, 78 m width and 18 m high. It is responsible for the stable operation of the pumps and adjusting radical water pressure changes that can result from an emergency rainfall. Each of fifty-nine pillars is 7 m long, 2 m wide and 18 m high, and weighs 500 tons. The pillars stand to support the cistern ceiling as if a shrine built under the ground.

The CNN television reported on the MAODC as a flood control measure to protect the Japan's capital for its relevance to Hurricane Sandy, which hit New York on November 1, 2012, "How giant tunnels protect Tokyo from flood threat!" The MAODC has actually the record of adjusting floods 85 times from the test service in 2002 to February 2014. The flood control effect obtained from the test service was remarkable, substantially reducing the damage due to the immersion in the Nakagawa River and Ayasegawa River basins.

According to past flood control records, Typhoon No. 3, that hit in July 2000 and dropped 160 mm of rain, devastated the Nakagawa River and the Ayasegawa River basins. Approximately, 137 ha area was flooded including 248 houses. However, with Typhoon No. 22 in October 2004, when the water escape to Kuramasugawa River has already started, the flood-related damage was substantially reduced, even though the amount of rainfall reached 199 mm. Approximately 72 ha area was flooded, including 126 houses. And with the flood caused by atmospheric depression hit the area in December 2006, when the water escape to the Oootoshi-furu-Tonegawa River had already been completed in June of the same year, flood-related damage was still more reduced the flooded area was approximately 33 ha and the number of flooded houses was 85, even though the amount of rainfall reached 172 mm.

In addition, in August 2008 when heavy rain storms were caused by the atmospheric depression, a time when the highest ever volume o inflow was recorded, flood control of approximately 11.72 million m^3 was available owing to the MAODC. Damage to the drainage basin was significantly reduced, which had been devastated by floods over the years.

The MADOC has remarkably reduced th flood damage anticipated in the Nakagawa Rive and Ayasegawa River development project resulting from the rainfall that may take place approximately once every 10 years (the average amount o 48 hours of rainfall in the drainage basin: 217 mm

Figures 7, 8 and 9 demonstrate the giganti underground shrine caves, which are amazing th civil engineers with wide open eyes.

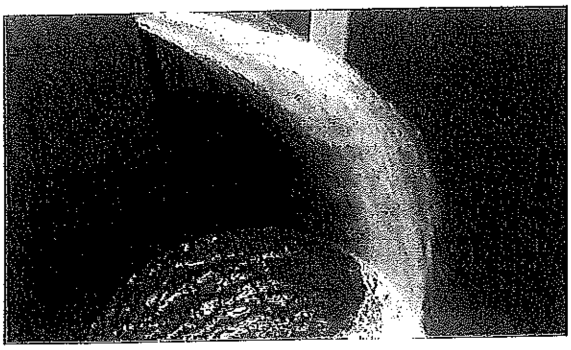


Figure 7. Flood water inflow to No. 5 bank.

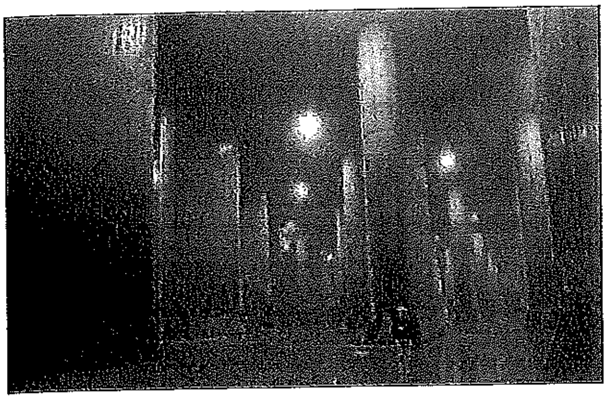


Figure 8. Gigantic underground shrine.

Figure 9. Gigantic pressure-adjusting water tank.

3 SHIELD TUNNEL ENLARGEMENT METHOD (STEM) FOR THE UNDERGROUND EXPRESSWAY

The innovative technology has been developed to connect main shield tunnel with ramp tunnel especially in urban tunnel construction, which was employed in the construction of the Metropolitan expressway in the central Tokyo area and the north of Yokohama area. As a result, the structures of underground junction and connection between the main shield and ramp tunnels can be constructed by excavation from the surface with a cut-and-cover method or trenchless method after main shield tunnels are completed.

With the development of this method, the distance of a tunnel excavated by one shield machine is dramatically increased and, overall construction cost is also reduced and the construction period is shortened compared with the tunnel construction by cut and cover method because of the constraint such as the installation of large-scale underground structures. In addition, the adverse effects on surface traffic and the surrounding environment can be reduced by minimizing the width of open excavation. Finally, it would be possible to minimize a risk for delay of the construction schedule and reduce environmental impact for surroundings.

3.1 *Outline of new structure*

Figure 10 shows the structure of the ramp or junction section constructed by the shield enlargement method with the cut-and-cover method.

The structure of the ramp or junction sections is much complicated due to the depth of excavation by the cut-and-cover method and the variation of the enlarged section shape along the longitudinal direction of the route. The typical structure of the merging and diverging section is shown in Figure 11.

This structure is a combination of the reinforced concrete frame body with relatively high rigidity and the steel segments with flexibility. These two components are connected with shear connectors welded to steel segments.

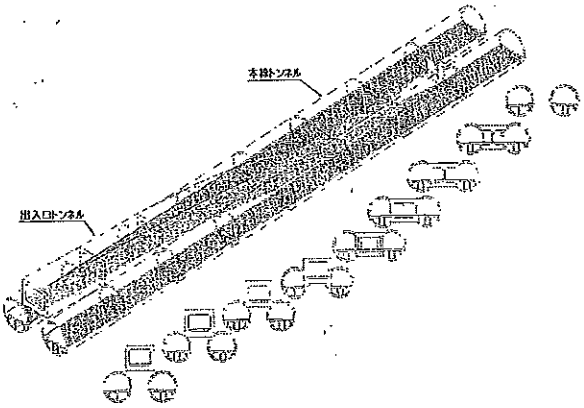


Figure 10. Overall structures of ramp section.

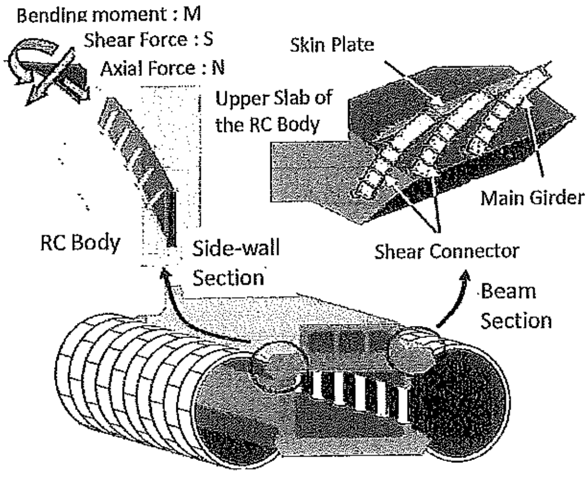


Figure 11. Typical structures of ramp section.

3.2 *Construction procedures*

Figure 12 shows the construction procedure for the sections of ramp or junction. In this procedure, earth retaining walls and water cut-off walls are constructed before the shield driving. Then, the ground above and between the shield tunnels is excavated from its surface after the tunnel has been installed with internal supports to prevent deformation of the segment due to the excavation.

The top slab, bottom slab and center wall are constructed while the ground between the tunnels is being excavated. Finally, the parts of the steel segments are removed.

In this procedure, since the excavation with the shield machine still continues after it passed by the section, as seen in Step 1, the work of cut-and-cover excavation with cutting the steel segments (as seen in Steps 2 to 6) is carried out simultaneously with segment supply and other works.

3.3 *Further development of STEM*

Currently, further development of the shield enlargement method by trenchless method has been developed, since the depth of enlargement section is very deep and there exist many structures on the ground. The cross section of the enlarged portion is shown in Figure 13.

From various trenchless methods, the mountain tunneling method is employed for enlargement of the shield tunnels for this site because the ground with high self-sustainability where the shields are located is composed of Neogene Pliocene or Quaternary Pleistocene rock. However, there are no the construction experiences in the urban area, FDA (Finite Difference Analysis) and measurement are carried out in order to verify the

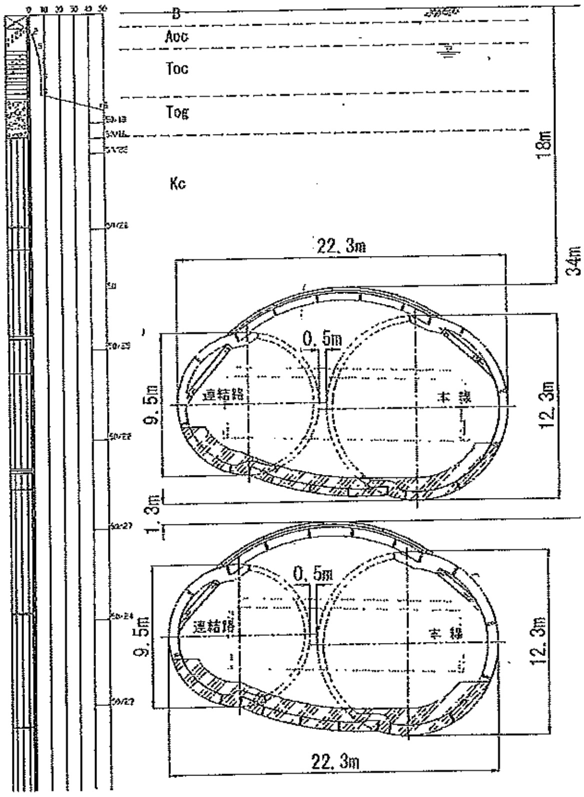


Figure 13. Cross section of diverging/merging portion

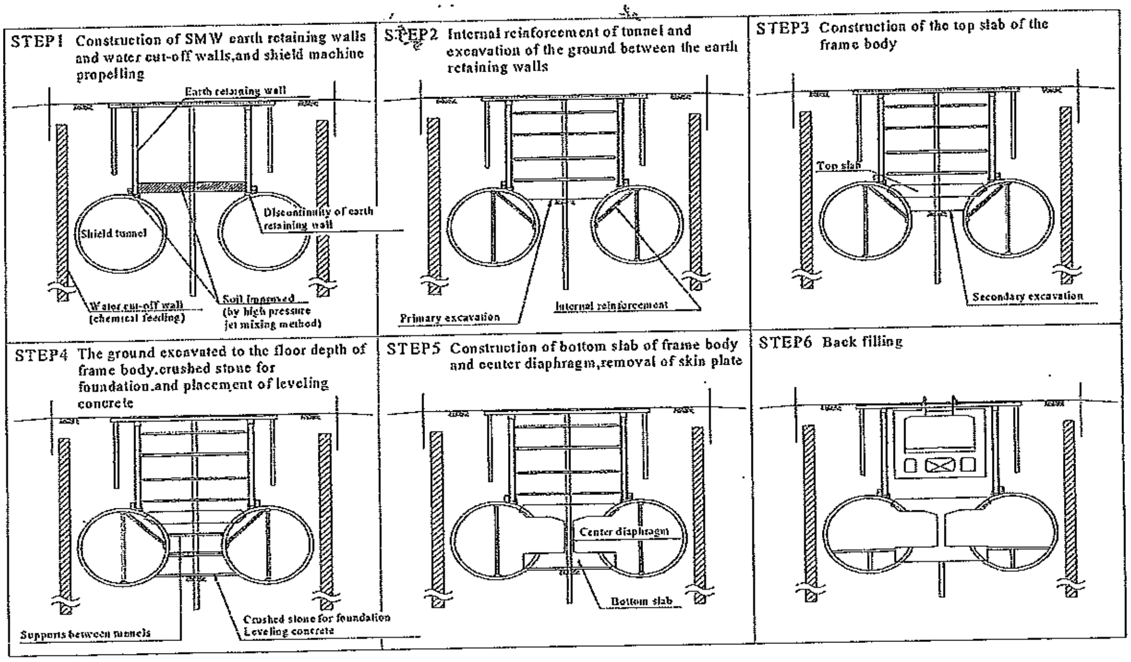


Figure 12. Construction procedure for the ramp and junction section.

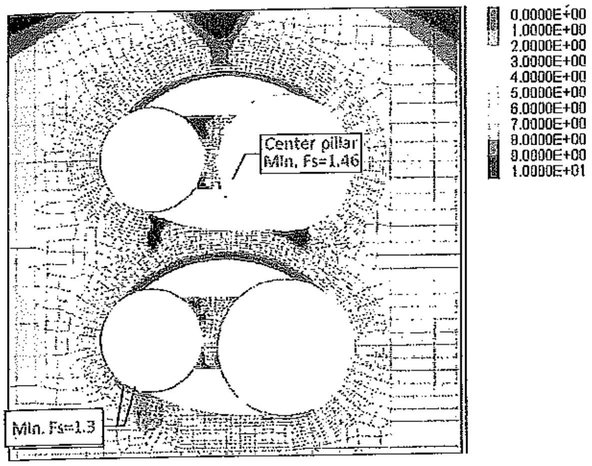


Figure 14. Safety factor for collapse of the ground and center pillar.

construction method during enlargement ensuring the stability of the face and the ground.

It is confirmed that the entire area of the face and above the face of the ground are an elastic state through all the construction steps. And safety factor (Fs) for collapses of the surrounding ground after completion of lower half excavation is calculated by Mohr-Coulomb yield criterion. It is verified that Fs of entire area surrounding ground and the center pillar are 1.3 and 1.46, respectively shown in Figure 14. Therefore, it is determined that the ground improvement is not necessary.

However, the exploration to check the cavity and significant loosening of the ground between two tunnels from the inside of the shield tunnel is carried out since the center pillar is very important to secure the stability of entire tunnel during enlargement. The results of measurements such as displacement of the ground, the stress of steel arch support, sprayed mortar and steel segment are less than design and calculated values.

3.4 *Perspectives of the trenchless tunneling method*

For the projects such as road and railway, deep underground space is expected to be more utilized in the future since effective utilization of urban space and reducing environmental impact will be required.

Those projects may need tunnel construction into the unconsolidated ground under high water pressure so that it is required to develop further advancement of shield tunneling technology and the lining design.

In addition, the innovative shield tunnel enlargement method will be more employed for the construction of merging and diverging section with the trenchless method.

In order to achieve the construction described above, further study on load such as earth pressure, the coefficient of the ground reaction and lateral pressure used in design, and analysis model and design method must be verified.

4 CONSTRUCTION OF THE TOKYO OUTER RING ROAD (GAIKAN)

4.1 *Summary of the construction project of the Tokyo outer ring road*

The Tokyo Outer Ring Road named as Gaikan, i.e. one of the three ring roads in the metropolitan area, is an arterial high-standard highway about 85 km long, for traffic in a radius of about 15 km from the metropolitan center (Figure 15).

The plan of the segment between Kan-Etsu Expressway and Tomei Expressway (approximately 16.2 km of the total length) was decided in May 2001.

This structure of the segment is the shield road tunnel almost "at great depths" based on the Law on Special Measures related to Public Use of Deep Underground. The tunnel covering this segment will be three lanes on each side and the largest shield road tunnel in Japan.

As a contacting facility, it has been planned to build Oizumi junction, Chuo junction and Tomei junction, connecting with Kan-Etsu Expressway, Chuo Expressway, and Tomei Expressway respectively. In addition, it has been planned to build Mejiro-Dori avenue interchange connecting with Mejiro-Dori avenue, Tohachi-Doro avenue interchange connecting with Tohachi-Doro avenue and Ome-Kaido avenue interchange connecting with

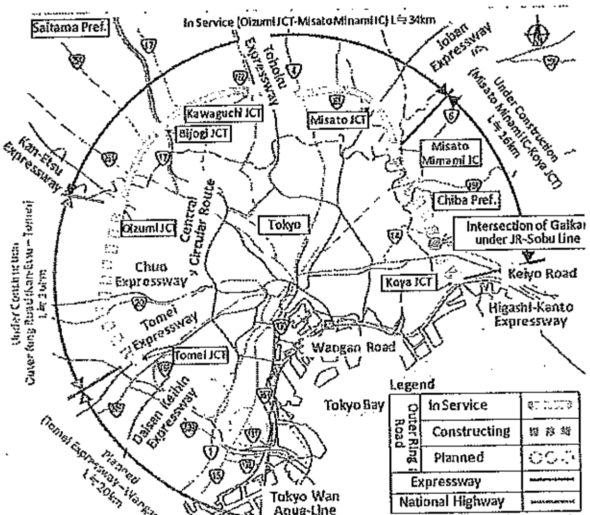


Figure 15. Overall plan and the arterial highway.

Ome-Kaido avenue. However, Mejiro-Dori avenue interchange and Ome-Kaido avenue interchange will become “a Half-Inter structure” that can get on and off only the direction of Tomei junction and the direction of Oizumi junction respectively (tentative name: Tomei junction, Chuo junction and each interchange).

4.2 *Law on special measures related to public use of deep underground*

In the Law on Special Measures related to Public Use of Deep Underground, it is possible to set usage rights for Deep Underground projects without prior compensation for public interest projects of roads, rivers, railway, telecommunications, electricity, gas, water, sewerage and other lifelines that are closely related to daily life.

Deep Underground refers to the space “at great depths” that is usually not used, as summarized by Figure 16:

i. depths generally not used in the construction of basements (40 m underground or deeper); or
ii. depths that are generally not used to build the foundations of high-rise buildings (10 m or more from the surface of the bearing strata).

The construction project is the second application case in Japan and the first case as roads based on Law on Special Measures related to Public Use of Deep Underground.

4.3 *Segment from Kan-Etsu to Tomei expressway (as of December 2016)*

The project has been approved “at great depths” on March 28th, 2014 and contracted to construct the four shield tunnels of the main road on April 3rd, 2014. East Nippon Expressway Co. ordered the main road bound for the south. Central Nippon Expressway Co. ordered the main road bound for the north. Each company ordered two shield machines. One starts from Oizumi junction and the other from Tomei junction. Now, the shield machines are implemented at Tomei junction and the departure shaft is constructed in Oizumi junction.

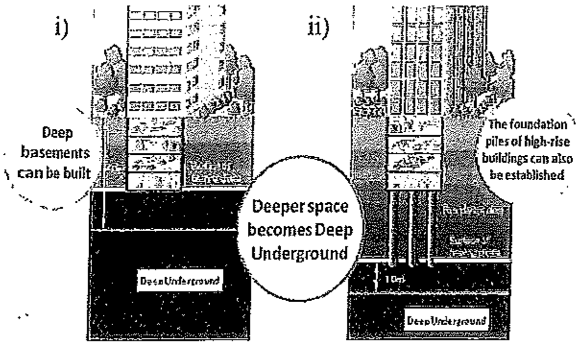


Figure 16. Deep underground according to the Law.

The soil stratum along the shield tunnel presented in Figure 17 is very hard as Kazusa-So-Gun soft rock. From Tomei junction to Oizumi junction, the cohesive soil layer (Kita Tama layer), sand layer (Higashi Kurume layer) and alternation of strata containing pebble, sand and cohesive soil layer inclining north are found.

It would be difficult for this shield tunnel to meet the requirements of “large cross-section, long distance, and high-speed construction,” and expect that the longer the distance of tunnel boring, the larger the risk that problems would occur. Considering the construction requirements of the tunnel and the expectation for early operation, the social adverse impact will be large if the risk becomes obvious.

Therefore, in order to achieve this safety, the start of tunnel boring from two portal sides are adopted (Tomei junction and Oizumi junction). In addition, in the case of unforeseen trouble during tunneling, the possibility to prolong tunnel boring distance can be taken into account with flexibility (Figure 18).

At places connecting tunnels to the Tomei junction, Chuo junction, and Ome-Kaido avenue interchange, it is necessary for the main tunnel to be en-larged underground without using the Cut & Cover method.

Due to the necessity of constructing the “underground enlarged portion” under the urban area, the committee set up a feasibility study to investigate the “basically circular geometry”, which is able to have “sufficiently wide zone of water cut-off performance”.

The water permeability of ground around the enlargement of underground at Chuo junction and Ome-Kaido avenue interchange is higher than at Tomei junction. Because there is the enlargement of underground at Chuo junction and Ome-Kaido avenue interchange under the low autonomy ground, it is required to work more technical and difficult construction. Therefore, the construction method will be decided after discussing and inspecting the technical issue further.

4.4 *Segment from Misato-Minami IC to Koya JCT*

This construction project is intersections part, where the Tokyo-GAIKAKU Expressway, i.e. Gaikan is currently constructed under the JR-Sobu Railway Line’s viaduct.

JR-Sobu Line is an important Railway for Tokyo metropolitan area, so a stop of the commercial line due to construction and allowing down of the driving speed are impossible. Further, the road shape constraints, it is not possible to deepen the depth of the road structures. And the space of road tunnel wasn’t prepared for the span of the railroad viaduct. In order to build a

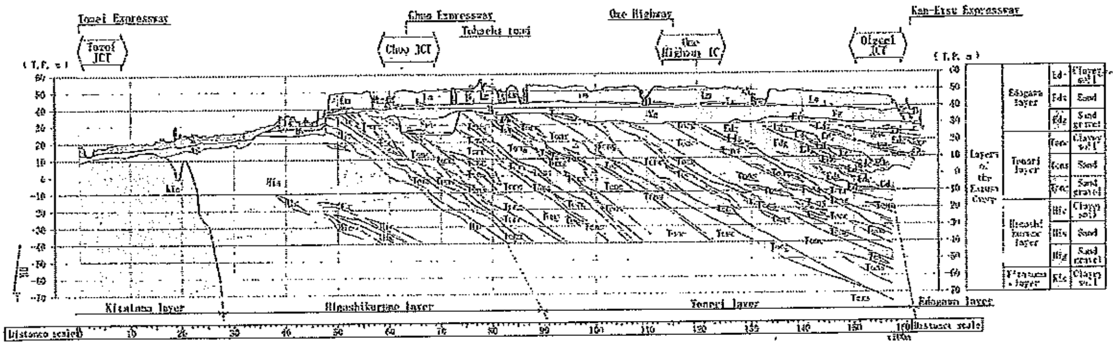


Figure 17. Geologic map along the route.

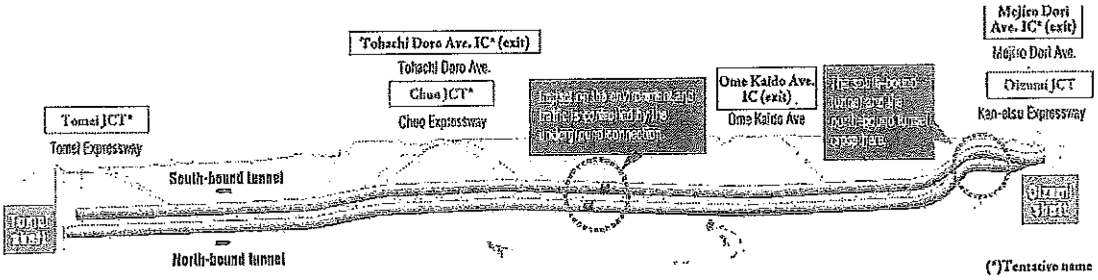


Figure 18. Longitudinal cross section of main shield tunnel and diversions.

road tunnel intersecting the railway viaducts, it is necessary to carry out renovation of viaduct simultaneously. However, for the renovation of the viaduct, it is necessary to construct it in the night, when a train operation has ended. Therefore, the construction cost and the necessary time period increase. In this project, to do the underpinning the existing viaduct and to renovate the long span viaduct, the new box culvert is constructed within the ground.

A completion image is shown in Figure 19. A four-lane Expressway at an underground part and a three-lane ordinary road above. a ground part are planned to be constructed in the section. An underground structure is box culverts of 1 layer and 3 spans.

Figure 20 shows the geological features at the construction site. The top 1.2 m is soft fill materials. Underlying fills are an alluvial sand layer of 4.2 m thick which irregularly contains silt and a diluvium layer which is an alternation of strata with sandy soil and clay soil extending from G.L. –5.4 m. The groundwater level is around G.L. –0.8 m.

Figure 21 presents an overview of the construction. The summarized construction steps are listed:

Step-1: large-scale box culverts (35.35 m in width and 19.75 m in length) on both sides of

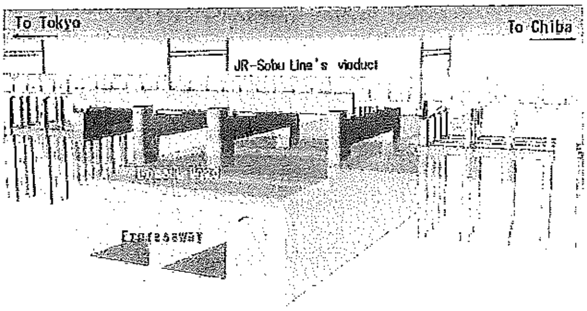


Figure 19. Completion image.

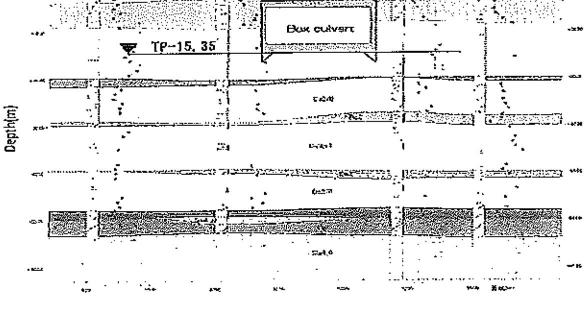
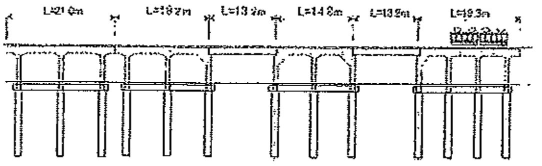


Figure 20. Geological features.

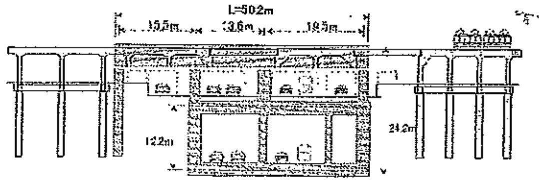
the existing railway viaducts by pneumatic caisson method have been built (Figure 22);

Step-2: bridge piers and supporting girders on the newly-constructed box culverts and existing girders, which supported the load, were replaced with the new girders by the hydraulic jacks. After that, existing pillars were cut and removed (Figure 23); and

Step-3: after the replacement of the load of viaducts, we built a box culvert in the central part by inverted lining method. Subsequently, 3 box culverts were connected and the tunnel structure was completed (Figures 24 and 25).



a) before



b) after

Figure 21. Overview of the construction.

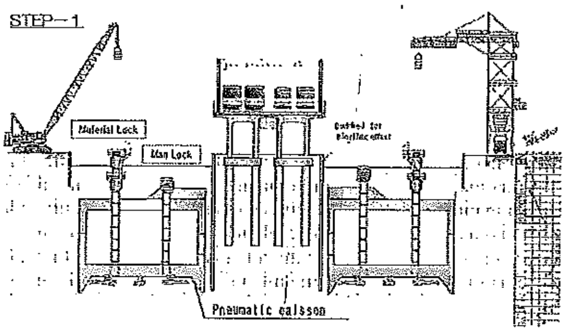


Figure 22. Step-1: pneumatic caisson method.

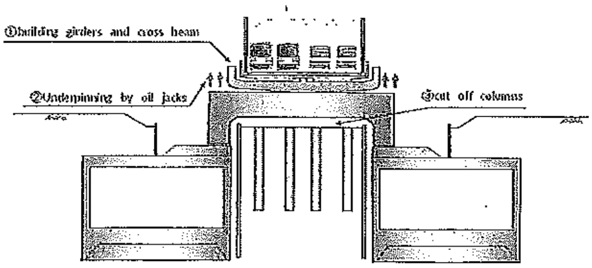


Figure 23. Step-2: superstructure building and underpinning.

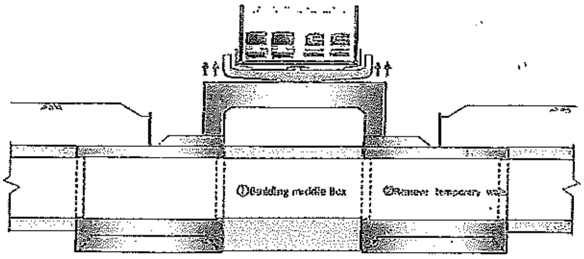


Figure 24. Step-3: connecting the three boxes.

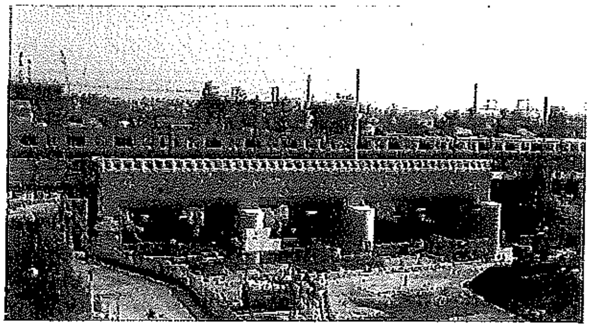


Figure 25. The completed structure.

5 CHUO SHINKANSEN CONSTRUCTION PLAN BY MAGLEV LINEAR

5.1 *Outline*

The Chuo Shinkansen is planned to be built as a new line between Tokyo and Osaka by maglev linear. It is opening the train track lines between Tokyo and Osaka in 2045.

Tokaido Shinkansen (300 km/h maximum speed) is the main track line, which runs already and takes 93 minutes between Tokyo and Nagoya, and runs in 142 minutes between Tokyo and Osaka. However, the Chuo Shinkansen (505 km/h maximum speed) is planned to run between Tokyo and Nagoya by the fastest service for 40 minutes and run between Tokyo and Osaka by the fastest service for 67 minutes.

There are 2 reasons for the construction of Chuo Shinkansen. The first is that the substitution line of Tokaido Shinkansen is needed, which passes an expected disaster area of the Nankai Trough massive earthquake. The second is that Tokaido Shinkansen needs the reconstruction with a long suspension.

A characteristic of a Chuo Shinkansen is using a run system of maglev linear, and for a special quality, a run route is to pass through Southern Alps Mountains (earth covering 1400 m, length of 25 km approximately of mountain tunnel) as straight as possible, also it uses the deep underground basically at Tokyo area and Aichi area. A tunnel section occupies the whole 86%.

5.2 *Route overview and the design*

Route longitudinal view between Tokyo and Nagoya is shown in Figure 26. Chuo Shinkansen with the extension of 286 km and the tunnel part of 246 km, includes the long mountain tunnel and the deep underground shield tunnel. Urban tunnel of the Chuo Shinkansen is in the Tokyo area that leads to the left bank of Sagamihara, Kanagawa from Shinagawa terminal station and in the Aichi area that leads to the terminal station of Nagoya from Aichi interval.

The Urban tunnel is planned to be constructed mainly by the shield TBM methods, except terminal station and the underground station in Kanagawa. Based on the special law mentioned in the Gaikan project, it is characterized in that passing through the underground 40 m deeper except for around the station unit. On the other hand, in urban areas, it is planned to provide an emergency exit with a diameter of about 30 m and depth of about 70~90 m, at about 5 km interval, for evacuation at the time of tunnel ventilation and emergency. That structure is expected to be the starting and the arrival shaft for the shield tunnel construction.

Standard sectional view of the shield tunnel is shown in Figure 27. Its cross section is compared with the conventional Shinkansen, which has a 20% greater cross-section and a tunnel inner diameter of about 13 m.

On the other hand, inside the emergency exit, placing the ventilation facilities for performing ventilation in the tunnel. In the ventilation facilities, placing a porous plate as a countermeasure to the micro-pressure waves and low-frequency sound, in addition to the ventilation equipment and the sound reduction equipment.

Also, placing the opening and closing facilities for wind pressure measures at the time of the train pass, and installing a refuge for the elevator and the stairs of the abnormality, and placing the elevator and stairs for the evacuation of the emergency. Overview of this emergency exit is shown in Figure 28.

5.3 *Planning of mountain tunnel*

Mountain tunnel section of the Chuo Shinkansen is employed at the Kanto Mountains and Tanzawa, the Koma Mountains, the Southern Alps Mountains, the Ina Mountains, the Central Alps Mountains and a hilly section. Many of the mountain tunnels are planned to penetrate the steep mountains with a deeply carved valley. In the Southern Alps and the Central Alps Mountains, the extension length is planned to be more than 20 km.

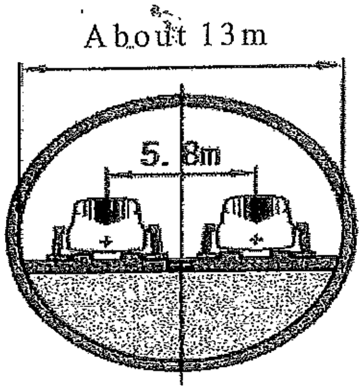


Figure 27. Standard sectional view of the shield tunnel.

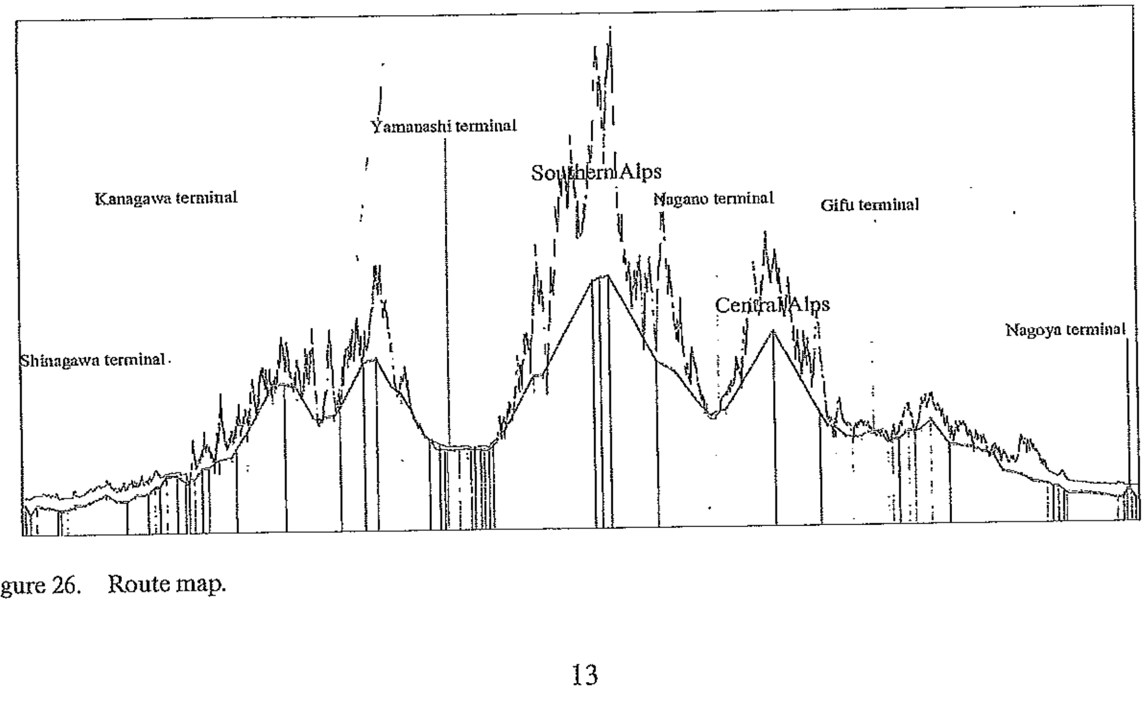


Figure 26. Route map.

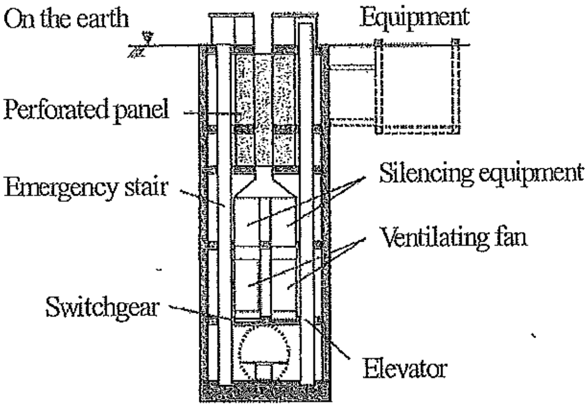


Figure 28. Overview of this emergency exit.

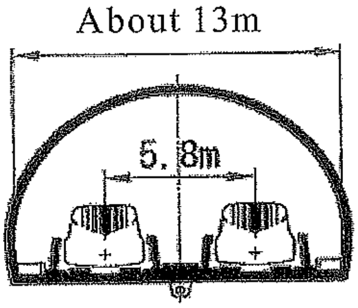


Figure 29. Standard sectional view of the mountain tunnel.

Standard sectional view of a mountain tunnel is shown in Figure 29. Its cross-sectional area is similar to that of the shield tunnel, which has 20% larger than the conventional bullet train.

Southern Alps tunnel is planned to be an extension of about 25 km. Geology is a Shimanto layer group and the Chichibu raw layer made of the sandstone and slate. The mechanical nature of the steep mountain is difficult to detect directly. Therefore, it is planned to drill a pilot tunnel that precedes the main pit. During the construction, the high-pressure spring water around the fracture zone and the rock extrusion by a huge rock stress are expected to be faced.

6 THE SOTETSU – JR AND THE SOTETSU – TOKYU THROUGH LINES

6.1 *Overview of the two lines*

Figure 30 shows a route map of two train track lines: The Sotetsu – JR through Line (SJ Line) and the Sotetsu – Tokyu through Line (ST Line).

The Sotetsu – JR through Line (SJ Line) is a project to construct a new connecting line (approximately 2.7 km) between Nishiya station on the

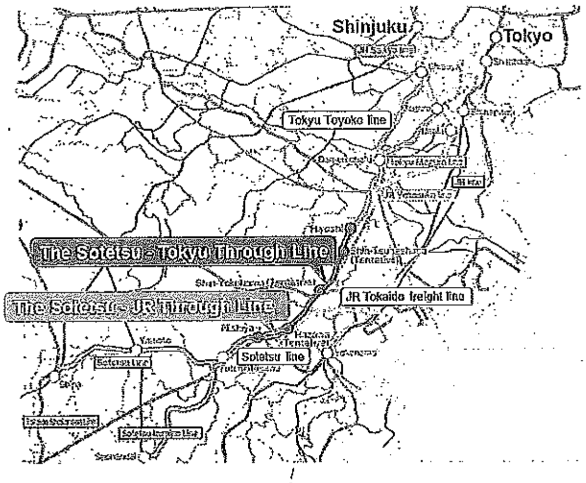


Figure 30. Overview of the Sotetsu – JR through line and the Sotetsu – Tokyo through line.

Sotetsu Line and a location near Yokohama-Hazawa freight Station on the JR Tokaido Freight Line. This connecting line will be used for through line operation that alternates between the Sotetsu line and the JR line. The construction project was approved in October 2009. Almost all of the 2.7 km between Nishiya station and Hazawa station (tentative) comprises an underground structure.

The Sotetsu – Tokyu through Line (ST Line) is a project to construct a connecting line (approximately 10.0 km) between a location near Yokohama-Hazawa station on the JR Tokaido Freight Line and Hiyoshi station on the Tokyu Toyoko Line. This connecting line will be used for through line operation that alternates between the Sotetsu line and the Tokyu line. The construction project was approved in October 2010.

These two routes are intended to form a wide-area railway network that directly connects the western part of Yokohama City with a central area of Kanagawa Prefecture and the center of Tokyo and to provide enhanced functions. When service begins, it will reduce travel time and the number of transfers needed, improving railway convenience and providing stimulation to the region and so on. It will also improve access to the bullet train and help further development in the Shin-Yokohama subcenter and other areas.

6.2 *SENS tunnelling*

Figure 31 shows the shield TBM machine (SENS). SENS is used in two tunnels on these two lines. In the first one is Nishiya tunnel on the Sotetsu-JR through the line, and the other is the Hazawa tunnel on the Sotetsu-Tokyu through the line. This chapter reports characteristics of SENS tunneling.

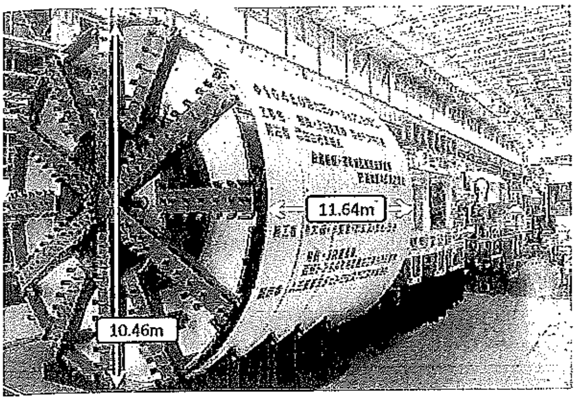


Figure 31. Shield machine (SENS).

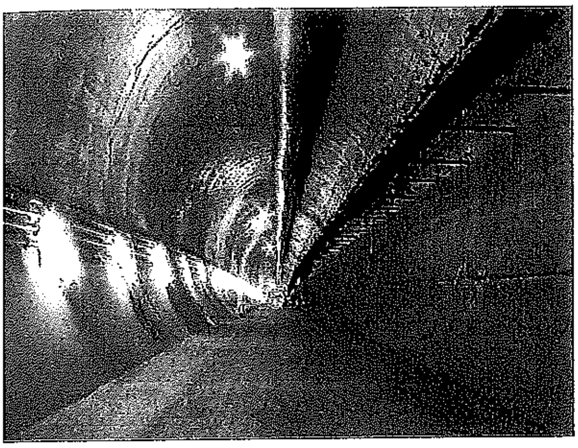


Figure 32. View after primary lining concrete placement.

"SENS" is an acronym formed from the first letter of each of these technologies: Shield Method + Extruded concrete lining + New Austrian Tunneling Method + System (Iida, 2008). SENS is a tunnel support system in which, while the ground is being initially excavated using a sealed earth pressure balance type shield tunneling machine (with the face being stabilized at the same time), concrete is pressurized at the shield tail section and placed to provide Extruded Concrete Lining (ECL) that will serve as the primary lining to support the tunnel, concurrently with the shield tunneling excavation.

Figure 32 shows the status after placement of the primary lining concrete. Subsequently, the stability of the primary lining is confirmed by taking measurements, and at the same time the New Austrian Tunneling Method is used to construct the secondary lining to complete the tunnel.

6.3 *Nishiya tunnel*

The Nishiya tunnel is a double-track railway tunnel of total length 1,446 m located between the Hazawa station (tentative) and the shaft near Nishiya station.

This is the third case of construction with SENS tunneling in Japan. The earth covering of the tunnel varies between 6 m and 46 m. The geological makeup of the section through which the tunnel passes is primarily the cohesive soil of the Kazusa Group (Km) (N value ≧ 35) interspersed with the sandy soil of the Kazusa Group (Ks) (N value > 50). One of the characteristics of SENS is that the primary lining is made of cast-in-place concrete, so the earth pressure at the face and concrete placement pressure could cause displacement of the ground surface. The Nishiya tunnel crosses under an arterial road (Route 16) with overburden of approximately 6.8 m. Route 16 has heavy traffic approximately 25,000 vehicles daily. Also, as shown in Figure 33, there are numerous utilities beneath the Route 16.

Widespread ground displacement would have an extremely large social impact, so, in this case, it was necessary to set appropriate limits for the earth pressure at the face and the concrete placement pressure in order to avoid affecting such facilities. Therefore, the method for setting control values for the earth pressure at the face and concrete placement pressure was determined based on the construction results in a trial zone provided within the starting yard. Based on the strictest primary control value for the gas pipes (±8 mm) and the maximum control value (±2 mm) obtained through ground surface measurements in the area with small overburden in the actual excavation, the displacement control target value was set at the value of ±4 mm.

Figure 34 shows the results for the two points with the largest displacement from manual measurements and the measurements made using settlement rods. Further adjustments in the pressure were made as work progressed, and an eventually excavation below Route 16 was completed without exceeding the primary control value of ±8 mm (Nakanishi *et al.* 2014 and Sakata *et al.* 2015).

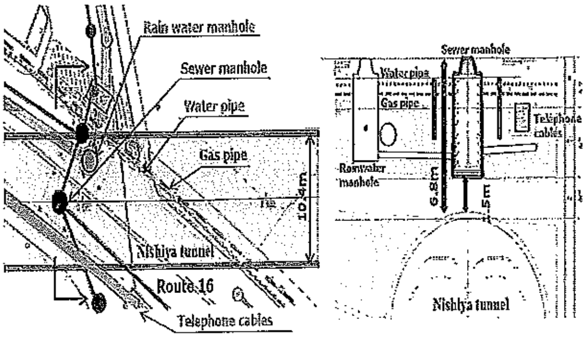


Figure 33. Plan and cross-section view of Route 16.

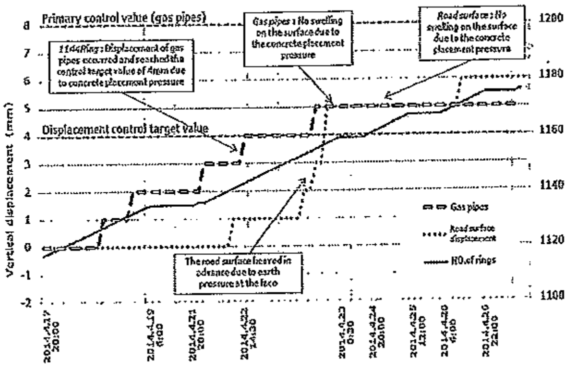


Figure 34. Manual measurement results of displacement for the road surface and gas pipes.

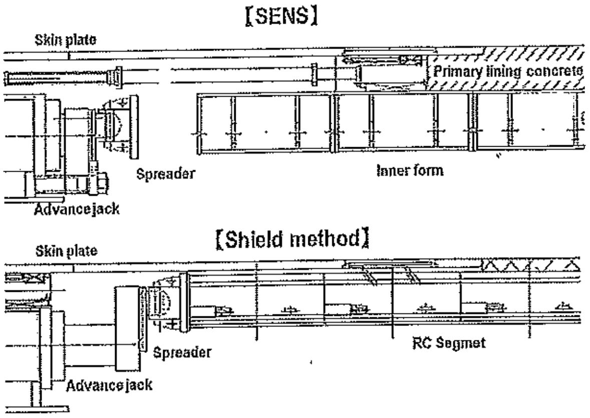


Figure 35. The jack positions during excavation both SENS and shield method.

6.4 *Hazawa tunnel*

The Hazawa Tunnel is a double-track railway tunnel of total length 3,515 m located between the shaft near Hazawa Station (tentative) and the Shin-Yokohama Station (tentative).

From Hazawa shaft there will be 166 m of cut and cover tunnel, and 3,349 m of circular tunnel. The circular tunnel section will be excavated by the mud pressure shield method, and both SENS and shield method segments were adopted as the lining. This tunnel approaches to closer than 1D to the foundations of the overpass of the Daisan-Keihin highway, the foundations of the viaduct and the piled foundations of the overpass on No. 2 Ring Road.

From the geology through which the tunnel passes is the same as Nishiya tunnel, it has been judged that the SENS can be applied to Hazawa tunnel. Also, the shield that was used on the Nishiya tunnel will be used on this tunnel to achieve further cost reductions.

Hazawa tunnel is a combination of cast-in-place lining and segments. Because, investigation of lining load resistance in reaching the side, as a result of the nearby effect analysis in the starting side, so it was not applicable in the cast-in-place lining. Accordingly, since the segment sections are on the starting side up to 529 m and 564 m from the arrival side, the SENS section is the remaining 2,256 m. Adopting segments for a part of the lining, so it is necessary to change a part of the shield device (hereafter referred to as the conversion).

Figure 35 shows the jack positions during excavation both SENS and shield method. The installation positions of the inner form and the segments are different, so it is necessary that the advance jack be compatible with both. Therefore, by enabling the spreader positions on the rod head of the advance jack to be changed, it is possible to use it for both inner form and segments.

The shield TBM was starting the excavation from the Hazawa side shaft on February 2016 and is currently also under operation. The construction will be carried out by paying great care not to adversely affect the important structures nearby.

7 SUBWAY TOZAI LINE MINAMI-SUNAMACHI STATION RENOVATION PLAN: PLATFORM/TRACK ADDITION

7.1 *Purpose of renovation plan*

Tokyo Metro Co. Ltd. ("Tokyo Metro") runs a subway network that comprises nine lines, 195.1 km of track and 179 stations, and serves the transportation needs of an average of 7.07 million people per day in Tokyo, one of the world's great cities.

The Tokyo Metro Tozai Line traverses the city center on the 30.8 km route from Nakano Station in western Tokyo to Nishi-funabashi Station in Chiba Prefecture (eastern Tokyo). The line began running in its entirety in 1969 and is used by an average of 1.41 million people per day, as recorded in 2015.

Through train services with two other railway companies are available from the Tozai Line, as shown in Figure 36.

The Tozai Line joins the Toyo Rapid Railway and the East Japan Railway Company Sobu Line from Nishi-funabashi Station, and the East Japan Railway Company Chuo Line from Nakano Station.

The number of passengers has increased each year as development progresses around stations of both the Tozai Line and the through train service lines. The passenger load factor during the morning rush on the most congested zone (trains heading toward western Tokyo) is extremely high, at 199% (measured in 2015), and there is an urgent need to mitigate delays.

Tokyo Metro is proactively revising schedules introducing wide-door trains, expanding platform

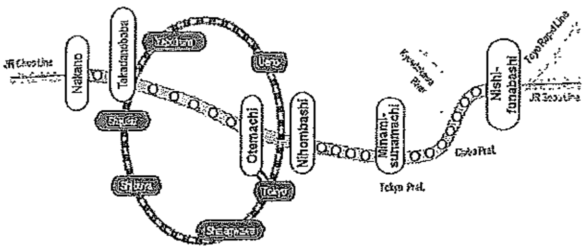


Figure 36. Tozai line overview.

and making other efforts to improve transportation on the Tozai Line. In particular, the development around Minami-sunamachi Station between 2005 and 2015 resulted in a roughly 40% increase in average daily ridership (from 45,442 people/day to 62,257 people/day), which represents a remarkable increase. This chapter describes a plan to renovate Minami-sunamachi Station to improve transportation on the Tozai Line and mitigate congestion on the station's platform.

7.2 *Background and local geology of Minami-sunamachi station*

Minami-sunamachi Station was built during a period of high economic growth in Japan. At the time, the surrounding area was an industrial zone, but the station was built there with future urban planning in mind. Renovation work to improve passenger services, namely adding entrances and establishing Barrier Free access routes from ground level to underground facilities, has been implemented sequentially since the station opened.

The station is located in the delta region of the Sumidagawa River, Arakawa River and Edogawa River, which comprises a deeply stratified and widespread alluvium deposit due to the effects of the rivers. Figure 37 is a standard cross-section that includes geological conditions. The layer from ground level to roughly four meters below consists of fill dirt, but below that is an extremely soft, cohesive alluvium deposit with N-values between 0 and 1.

The pneumatic caisson method was used to construct the station because it was located beneath the Susaki-gawa, a canal that connected to the former coastline. However, development around the station progressed and the canal was reclaimed in 1988 as part of a strategy for more effective land use. Now Minami-sunamachi Station lies beneath roads and privately owned land.

7.3 *Minami-sunamachi station characteristics and renovation plan overview*

Presently, Minami-sunamachi Station comprises one platform between two tracks, and station

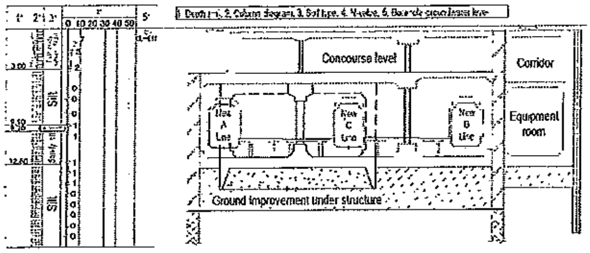


Figure 37. Standard cross-section, with geologic conditions.

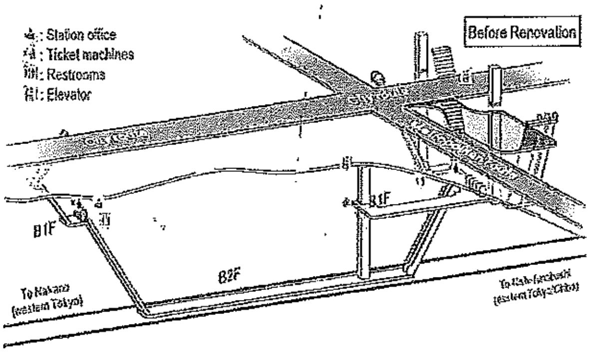


Figure 38. Present state.

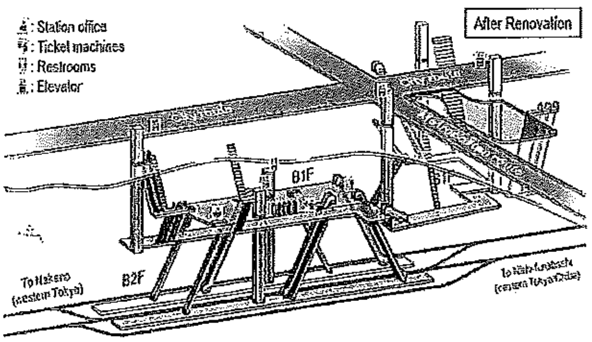


Figure 39. After completion.

spaces and vertical transportation facilities between the ticket gates and platform are concentrated at each end of the platform as shown in Figure 38.

The following measures will be taken under this renovation plan in an effort to improve transportation on the Tozai Line and mitigate congestion on the station platform (see Figure 39).

1. Relocate platform stairways: relocate and increase the number of stairways in the center of the platform to disperse the passengers climbing and descending them in an effort to improve their safety;
2. Relocate station spaces: relocate passenger waiting areas, restrooms, and other station spaces to the center of the station and expand facilities in an effort to improve services; and

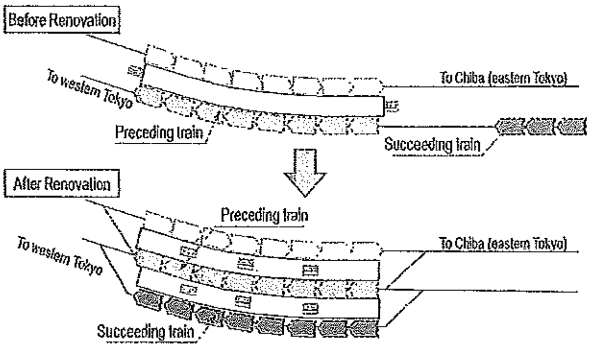


Figure 40. Functionality to mitigate delays.

3. Add one platform and track: total of two platforms and three tracks as shown in Figure 40, in an effort to equip the station to absorb delays, accomplished by reconfiguring the station such that the succeeding train can enter the station during delays caused by the time required for passengers to exit and board the preceding train.

7.4 *Countermeasures for construction in soft ground*

This renovation work involves using the open-cut method within an extremely soft, cohesive alluvium deposit. As countermeasures, a very rigid, reinforced concrete diaphragm wall to be kept as part of the main structure is being used, and the ground beneath both the existing and new structures is being improved (design strength: at least 1 MN/m^2) using the high-pressure injection and stirring method as shown in Figure 41 to function as footing beams for restricting deformation in retaining walls during excavation and to prevent subsidence during construction of the new structure.

The ground improvement work under the existing structure is being performed from inside the structure with the small ground improvement machine shown in Figure 42 to retain the weight of the earth above the existing frame in an effort to keep the existing structure from rising and skewing the track alignment or damaging the structure.

However, the fact that the ground improvement is being performed with a machine located inside the existing structure limits the working hours to the two-hour, 50-minute period from 1:10 to 4:00 when trains are not operating.

Construction for this renovation work is in progress. The goal is to complete it in time to put the new structure into service in 2021. At present, the reinforced concrete diaphragm wall is being built in preparation for excavation, and the ground improvement work beneath the structure is under way. Further excavation of extremely soft ground lies ahead, and the goal is to work in earnest, while placing the utmost priority on ensuring the safe operation of Tozai Line trains.

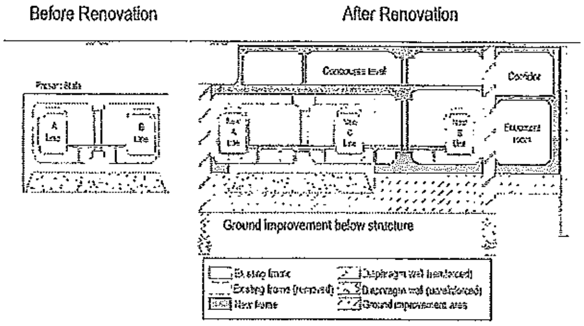


Figure 41. Comparison of standard cross-section.

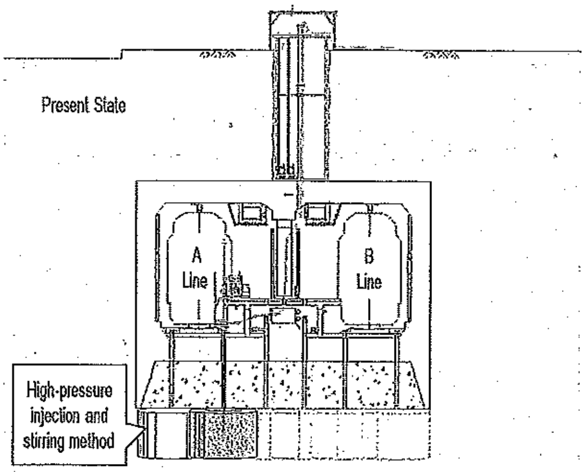


Figure 42. Ground improvement work within existing structure.

8 CONCLUDING REMARKS

This paper summarizes the geotechnical aspects of current underground construction activities in Japan, which are amazing the international geotechnical engineers with wide open eyes.

Included are the MAODC, the expansion and the production of the underground expressway, Chuo Shinkansen bullet train, the connection of the new urban train system and the renovation of the existing subway station, in order to demonstrate the active underground construction for the Tokyo Olympics in 2020. The followings are the concluding remarks on the listed underground construction.

1. MAODC has been built with the large underground shrine cave and been utilized to reduce the flood damage of the north of Tokyo area.
2. Metropolitan expressways have been built with the large diameter shield TBM and the *in-situ*

expansion of underground space without the cut and cover method.

Gaikan expressway project will be finished with the large diameter shield TBM tunneling and the large underground space production with the underpinning.

  i. Pneumatic caisson method: a construction condition was seriously severe because the separation was only 2.0 m between newly-built box culverts and the foundations of the existing viaduct. Afterward, we confirmed the influence on the viaduct by 2D Finite Element Method in advance and a countermeasure based on the consideration results was devised, and then the construction works were completed safely. Isolation barrier wall was constructed between the viaduct and the box culvert in order to reduce the negative influence. The protection work was constructed by BH method ($\varphi = 0.5$ m) at a distance of 0.7 m from the box. Also, the heads of the protection work were connected each other to prevent the ground surface settlement during the caisson work. Four press-in ground anchors were used together to prevent the inclination and loosening of the ground and to improve the construction accuracy.
  ii. Underpinning: the 52 oil jacks were distributed on newly-built girders and piers and then load supported by the existing piers were replaced with new ones step by step. Rubber shoe and stopper were set on each shoe seat and after the girder structure was completed, the piers of the viaduct were cut and removed. During the replacement work, we could restrain the displacement of the existing viaduct within the range of the allowed value in train operation.

4. SENS tunneling method has been utilized for the underground construction of urban train track system, which connects the existing train systems.
5. Tunnel group construction of Chuo Shinkansen is quite difficult, when viewed from the tunnel construction achievements in Japan and includes the long shield tunnel in the urban areas and the mountain tunnel. The development of the future of the construction plan, using the latest technology related to measurement evaluation and construction methods as much as possible will reduce the impact on the environment and achieve the safety and economic efficiency.
6. Old existing subway system has been renovated with the underground geotechnical construction technology in soft ground.

In Japan, lots of larger cross-section, longer span and deeper underground construction projects are planned and conducted under densely populated urban area with soft ground and complex proximity conditions. These geotechnical engineering experiences mentioned here and the geotechnical engineers are sure to contribute the development of worldwide underground construction projects in soft ground.

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