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Advanced technologies for construction: a large scale repair and renovation of the metropolitan expressway network

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ABSTRACT: The first section with 4.5km length of the Metropolitan Expressway opened in 1962 to reduce traffic congestion in the city center of Tokyo. And until 1962 when Tokyo Olympic game was held, about 33km of the network were opened. Today, the Metropolitan Expressway network plays an important role as major traffic facility that supports socio-economic activities in the Tokyo metropolitan area and it currently extends for approximately 310 km. Among those, 95% of the network is comprised of the structures such as bridges, tunnels and semi-underground structures, and 30% of the structures have passed more than 40years after opening to traffic. In recent years, for deterioration of the urban infrastructure and a large-scale disaster such as large earthquake, appropriate operation, maintenance, retrofit and renovation works are highly required in addition to development of the expressway such as circular road for effective utilization of existing network. In this paper, advanced construction technology for the expressway with consideration of environmental conservation in highly developed urban area are described and the project of a large scale repair work and renovation of the Metropolitan Expressway are introduced.

1 INTRODUCTION

1.1 *Metropolitan Expressway Network*

The Metropolitan Expressway network serves as a principal traffic infrastructure that supports socioeconomic activities in the Tokyo metropolitan area, and it is a road network system that is indispensable to the community and the lifestyle of the people in the area since 1962 when the first section of the expressway was opened. The network of the Metropolitan Expressway currently extends for 310 km. It carries about one million vehicles per day and heavy vehicle traffic reaching five times that on the roads of Tokyo's 23wards.

Of the route on the network, some 40% (approximately110 km) has been in service for more than 40 years while some 50%(approximately 160 km) has been in service for 30 years, which means the expressway has been aging. In addition, some 95% of the Metropolitan Expressway (Shutoko) is comprised of the structures which require extremely detailed maintenance, such as viaducts, bridges and tunnels, etc., which is a percentage markedly more than other ordinary roads(see Figure 1 and 2).

1.2 *Central Circular Shinjuku and Shinagawa Routes*

The Central Circular Route is one of the "three circular expressways in the Tokyo metropolitan area", together with the Metropolitan Inter-City Expressway and the Tokyo-Gaikan Expressway. It is the innermost circular expressway located within a radius of approximately 8km from the city center of Tokyo. On March 7th 2015, construction of the last section of 9.4 km, central circular Shinagawa Route was completed as shown in Figure 3. Finally, the entire route of Central Circular Route is in service with total length of about 47 km, including a tunnel section of 18.2 km which is the second longest road tunnel in the world.

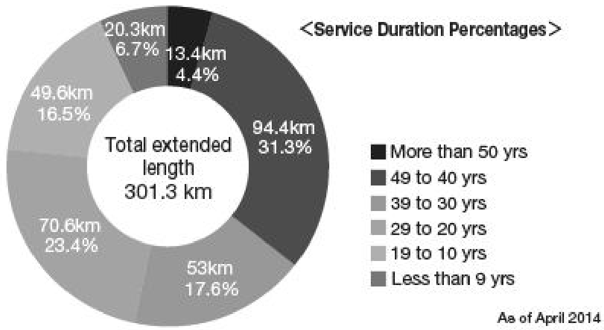

Figure 1. Percentage of in-service period

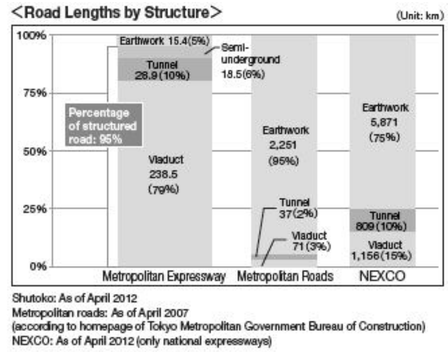

Figure 2. Ratios of structure length

By the completion of the central circular route, the following direct effects are expected to

1) Control the flow of through traffic into the central area
2) Detour and disperse traffic traveling from the suburbs to the central area
3) Enable direct travel among surrounding areas
4) Perform redundancy in case of accidents or disasters
5) Carry out improvement in air pollution due to smoother traffic flow.

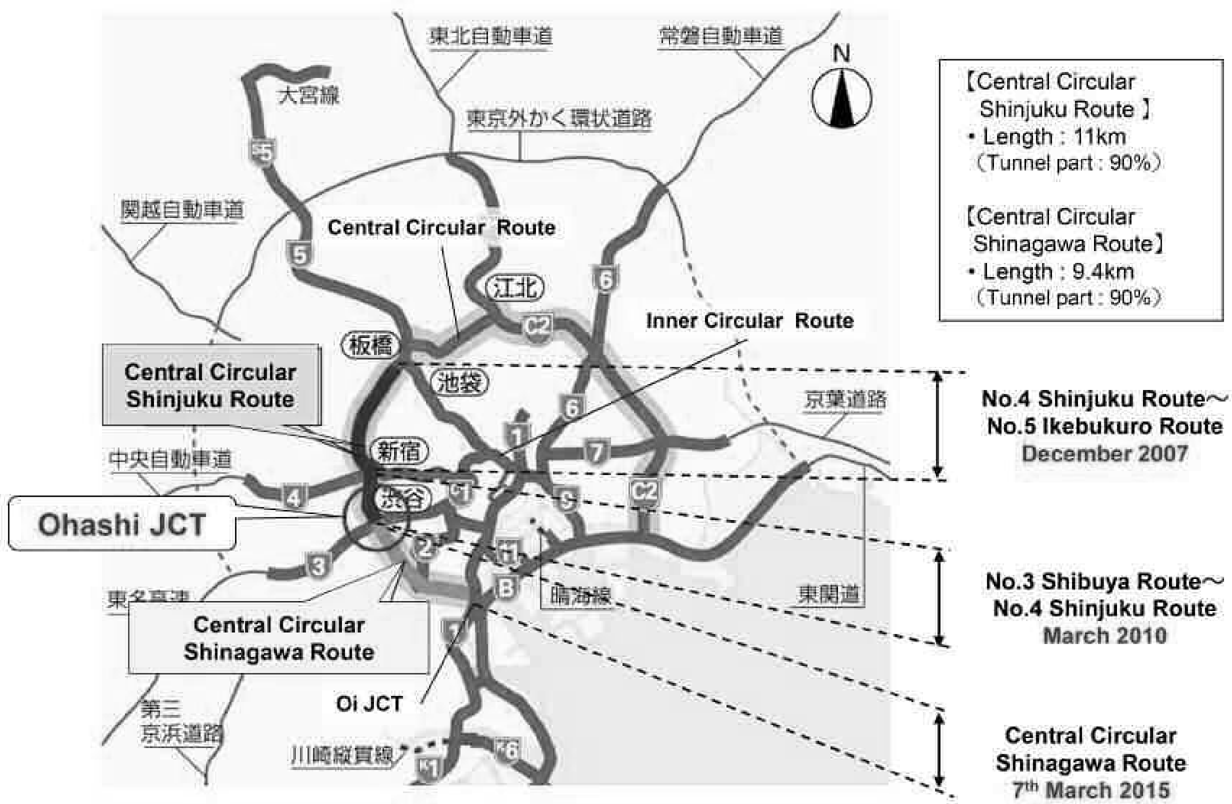

Figure 3. Metropolitan Expressway network in Tokyo area

The Shinjuku Route is an 11 km expressway that is designed with two lanes in each direction and has a design speed of 60 km/h. To accommodate the land use patterns along the route, and in order to preserve a sound environment and make efficient use of limited public urban space, the Shinjuku Route is designed as a tunnel structure under the circular road Route No.6, which will be widened to 40m in the same period. Therefore, the alignment of the tunnel, the types of underground structures, and the construction methods must take into account constraints such as the crossing of rivers, subways, trunk roads and railways, as well as the accommodation of major existing public utilities. As is typical with urban expressways, it has a short average distance between the access ramps, with six access ramps to the ground-level street and three junctions with radial routes of other Metropolitan Expressways.

When the Shinjuku Route was planned in 1985, a large diameter shield tunnel accommodating an expressway greater than 13 m in diameter had never been constructed, so that the construction method for the

Shinjuku Route tunnel was originally planned to be a cut-and-cover method. However, in the 1990's, shield tunnels with 14m in diameter were built, and recent developments have been made in construction methods for underground junctions for entrances and exits. Therefore, the construction method for approximately 80% of the entire tunnel has been changed from a cut-and-cover method to a large diameter shield tunneling method.

On the other hand, the Shinagawa Route is a 9.4km expressway between Oi junction of Bay Shore Route and the Shinjuku Route. It was originally planned 8km long distance shield tunnel based on the experience of shield tunnel construction of Shinjuku Route to mitigate traffic congestion during construction. It was also designed with two lanes in each direction and has design speed of 60 km/h as well. It includes very complicated large scale underground structures such as 4 ventilation stations, 2 junctions and 2 access ramps.

2 ADVANCED TECHNOLOGIES FOR CONSTRUCTION

2.1 *Long Distance Advancing Shield Tunnel with Large Diameter*

In urban areas such as Tokyo metropolitan, the land surface area for the tunnel construction is limited. Therefore, even the shaft for shield tunnel should be reduced and the employment of trenchless method is required as far as possible. As a result, 8km long distance shield tunnel with large diameter was employed for the Shinagawa Route.

Long distance shield tunnel is also required rapid advancement. The durability of equipment of the shield machine; for instance, main bearing, tail seal and screw conveyor, must be secured to achieve long distance advancing. A shield machine is also required to equip cutting bits which can be used for both gravel layer and hard clay layer. To achieve rapid advancing, improvement in advancing speed and assembly speed of the segment are important. In addition, maintenance plans for securing the capability of equipment which transport segment and excavated muck is also important factor.

2.2 *Enlargement Method of Shield Tunnel*

The use of the enlargement method of large dimensional shield tunnel construction is essential in the construction of connection between main shield tunnel and ramps, particularly when constructing underground roads in narrow urban areas. The construction method that involves cutting and removing part of steel segments is employed. Even for the sections where the shield tunneling method is used, it is still necessary to install escape routes, pump rooms, ducts, and structures at branch junctions. In order to build these facilities, shield segments must be partially removed and enlarging shield tunnel to provide an underground space larger than the tunnel itself. Specifically, enlarging shield tunnel construction is to be carried out between two parallel tunnels for a single span of up to 500 m at 5 locations in order to construct connection between main shield tunnel and junctions for entrances in Shinjuku Route (refer to Figure 4); the total length of such enlarging shield tunnel sections will be 1.3 km. This shape of extremely long, large-scale, and structurally complicated enlarging shield tunnel construction was unprecedented.

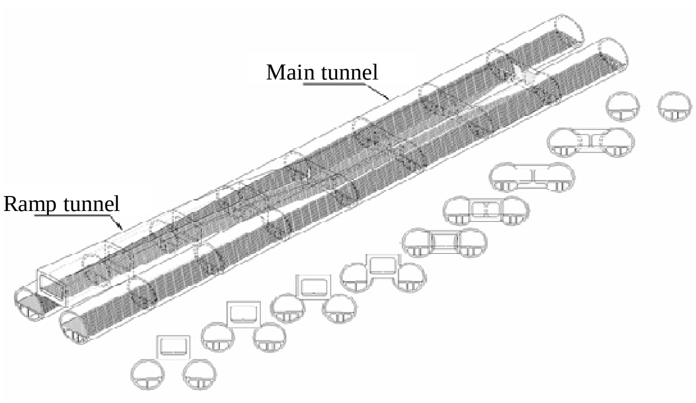

Figure 4. Enlargement of shield tunnel cross section

There are two possible construction methods. One is the cut and cover method to excavate from ground level to allow the construction of access ramp structures at the side and top portions of the shield tunnel. The other method is the trenchless method where adjacent vertical shafts are used to support the upper ground by employing roofing pipes, the ground between the two tunnels is then excavated from the spaces provided above both tunnels, and finally the access ramp tunnels are constructed between two shield tunnels. The cut and cover method is generally used in the enlargement of shield tunnel construction for the Central

Circular Shinjuku Route. However, the trenchless method is applied when the cut and cover method would significantly impact on surface traffic and/or it is difficult or time consuming to adequately deal with the various underground installations. Regarding the construction of the roofing portion, three different methods are used at three different locations, i.e., the parallel pipe roof method, to arrange pipes parallel to the tunnels; the curved pipe roofing method, to arrange pipes in transverse directions; and the NATM method. In this paper, the shield enlargement with trenchless method for the construction of the underground junction of "Ohashi Junction" is introduced.

2.3 *Execution of Shield Enlargement with Trenchless Method*

Ohashi Junction forms the branch junction with diverging and merging portion below the densely urban area, and is of an upper and lower double layered structures. This ramp tunnels were constructed by shield tunnel method beside the main shield tunnels. After driving shield tunnels, by connecting the main tunnels with the ramp tunnels together over the length of about 200m, the underground junction was constructed safely with little effect on the ground above. The plan view of Ohashi Junction is shown in Figure 5.

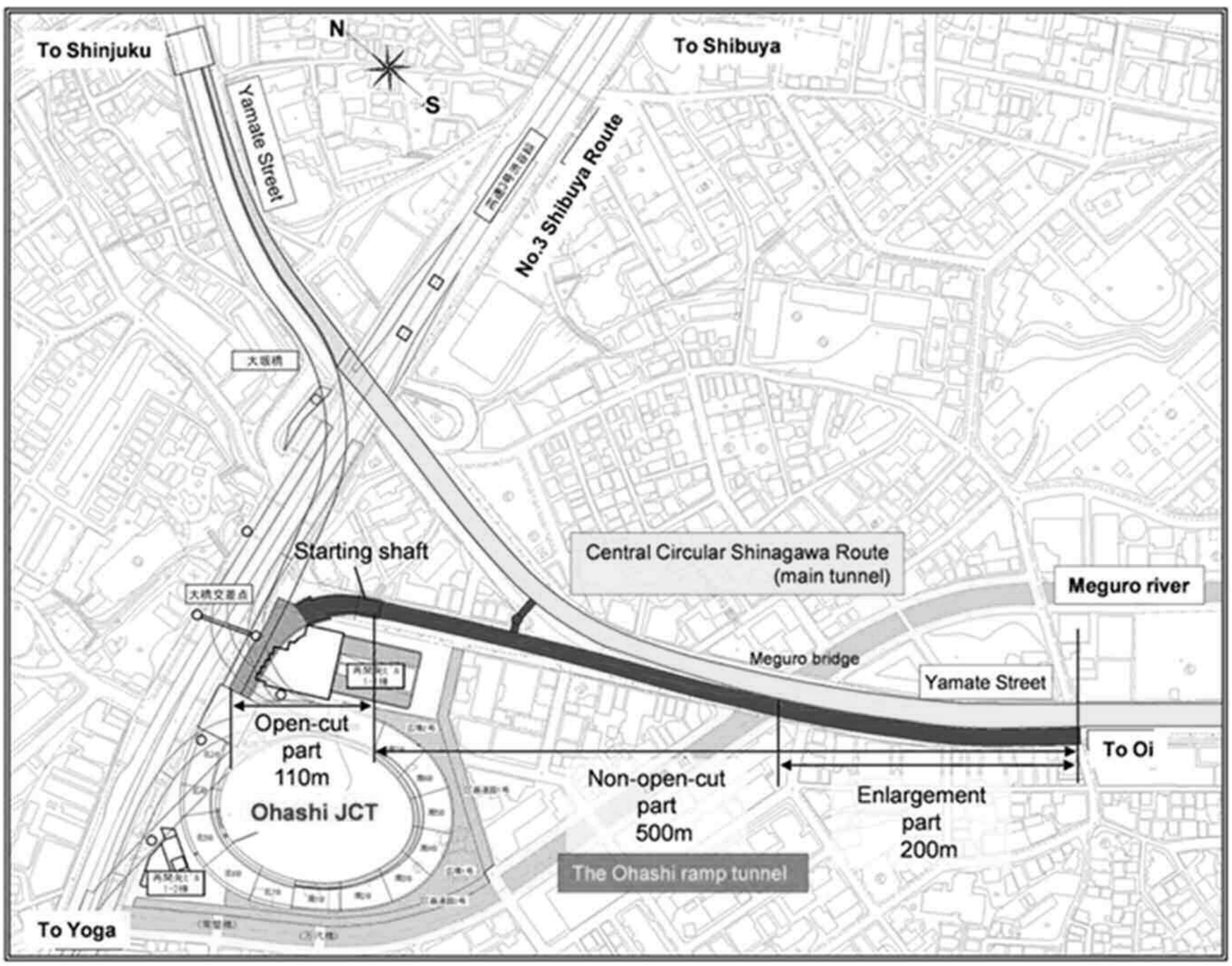

Figure 5. Plan view of Ohashi junction

In the enlargement of two shield tunnels, the innovative method was developed by arch-shaped segment, and enabled economical and efficient construction with little effect on surrounding environment. In the shield section, about 200 m on the arrival side of the shield machine forms branch junction section. In this section, a total of four shield tunnels are constructed since the ramp tunnel is a double-layered structure. After shield driving, the space between the main tunnel and the ramp tunnel was enlarged by the trenchless method such as NATM (New Austrian Tunneling Method) to build a huge oval-shaped space as big as a little more than 250m^2 (see Figure 6). Furthermore, the minimum distance between the main tunnel and the ramp tunnel is 0.5m, and the distance between the upper and the lower tunnel is 1.3m at its minimum (see Figure 6). Therefore, the construction with high precision was required.

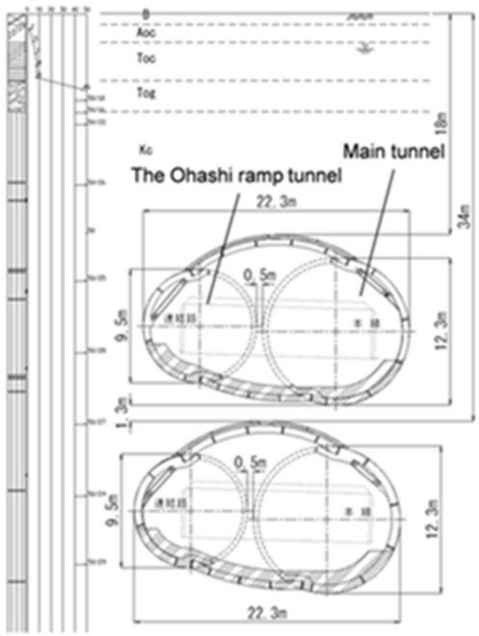

Figure 6. Cross section of junction

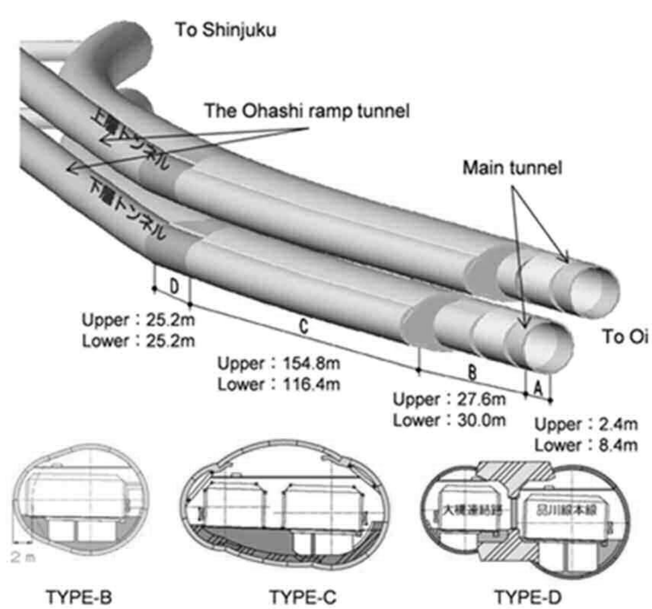

Figure 7. Ohashi ramp tunnels

This enlargement section is located below “Yamate Street” with a daily traffic volume of 40,000 vehicles. Along this street stand together a number of buildings, and there are important structures such as overpass and river. With consideration of these factors, since enlargement work by cut and cover method from the ground adopted in the Shinjuku Route was difficult, enlargement work for the underground junction by trenchless method was employed. The depth at this site as deep as 30-50m was also one reason that the trenchless enlargement method was selected.

Cast-in-situ lining concrete mainly adopted in the Shinjuku Route is not employed as a lining, but the oval structure which connects between the main tunnel and the ramp tunnel by arch-type steel enlargement segment (“arch steel shell”) is employed. By using the arch steel shell as lining, securing of high water tightness and durability, shortening of construction period by improvement of workability in narrow space are aimed at.

For branch junction, four types of lining structure were designed to meet the variation of required inner width (9m-17m) (see Figure 7). These are four types such as TYPE-A which does not require enlargement because of allowance of inner section of the main tunnel, TYPE-B which partially enlarges the width of 1-2m by enlarging the side part of the main tunnel and using steel enlargement segments, TYPE-C which constructs a large-diameter column-less section integrating both tunnels by arch steel shell after enlarging the ramp tunnel and the main tunnel which travel in parallel, and TYPE-D which integrates both tunnels by cast-in-situ concrete structure in the one-column section of the ramp tunnel and the main tunnel beyond the nose.

In enlargement work, not only the analysis of various structures and the ground, but also confirmation of the safety and workability of the method by model tests with 1/2 scale were conducted. In construction as well, various methods such as method of construction in narrow space and safe construction procedures for the distance of 1.3 m between two tunnels in the upper and lower section of branch junction were conducted as well as measurement of displacement, deformation and stress conditions, etc. As the two tunnels which were driven in parallel are closed by arch steel shell, it is required that the construction error such as the meander, the rolling and the gap of the section in vertical direction is controlled. Furthermore, it is measured between the two tunnels after excavation, and the shape of each arch steel shell is determined by the result of measurement in order to absorb the still remaining error and displacement of tunnels after excavation.

Measurement of the settlement is conducted to assess the effect on the ground surface structures and the underground piping. Rivets for measurement are installed on the road to measure ground surface settlement. Displacement is measured by level survey one time per day. At any time of measurement during construction, measured values remain within 5mm of primary control value.

The settlement gauges, inclinometers and thermometers are installed in the abutment of the Meguro Bridge to measure vertical displacement and inclination of the abutment associated with construction. Thermometers are used for compensation of measurement errors due to the temperature of measurement points and fixed points. The measurement is carried out until one month after a period that the effect of enlargement work is expected, and ends after confirming convergence of measurement data. At any moment of measurement, measurement values remain within 5mm of primary control value.

2.4 *Shield Launching from the Ground Level*

Another innovative method in shield tunnel construction has been newly studied, developed and implemented in the actual tunnel project of Shinagawa Route. This method named URUP (Ultra Rapid Under-Pass) enables TBM to launch and arrive at ground level without vertical shaft. This method enables to construct the underpass in short construction schedule and to mitigate the impact on the adjacent structures by large scale excavation as compared with cut and cover tunnel method. The shield machine for this method drives under a shallow overburden as shown in Figure 8.
The expected advantages of this method are the followings.

i. To reduce the tunnel section with cut and cover method
ii. To minimize impact on existing adjacent structures
iii. To minimize environmental impact

Tunnel construction sequences are as follows,

1) The shield machine launches from the ground level, and arrives to Oi-Kita Ventilation Station for Ohashi-bound tunnel.
2) The shield machine turns around in the ventilation station and to be elevated to the re-launching position of construction of Oi-bound tunnel
3) The shield machine re-launches from the Ventilation station and arrives to the ground level for Oi-bound tunnel.

Figure 8 shows the tunnel construction sequence. For the construction sequence, the followings are important technical items in the planning of this method in Oi Area tunnel.

a) Temporary equipment for TBM launching

The shield machine of this method can be launched from a shallow pit below the ground. Consequently, earth pressure and underground water pressure on the shield machine are small. Therefore, the entrance packing, temporary lining segments and heavy reaction truss are not required. Only simple reaction truss with small amount of steel pipes or H-beams should be used for launching of the shield machine in this method. As a result, the launching thrust force of the shield machine in Oi Area Tunnel construction is 25% of the total capacity of thrust force.

b) Lining support structures at the launching/arrival points

The lining segments without vertical pressure in launching/arrival or small vertical pressure with shallow overburden have different sectional forces and deformations as compared with the lining segments with certain amount of overburden. In order to minimize this sectional force and deformation of the lining segments, temporary and permanent support structures shall be installed.

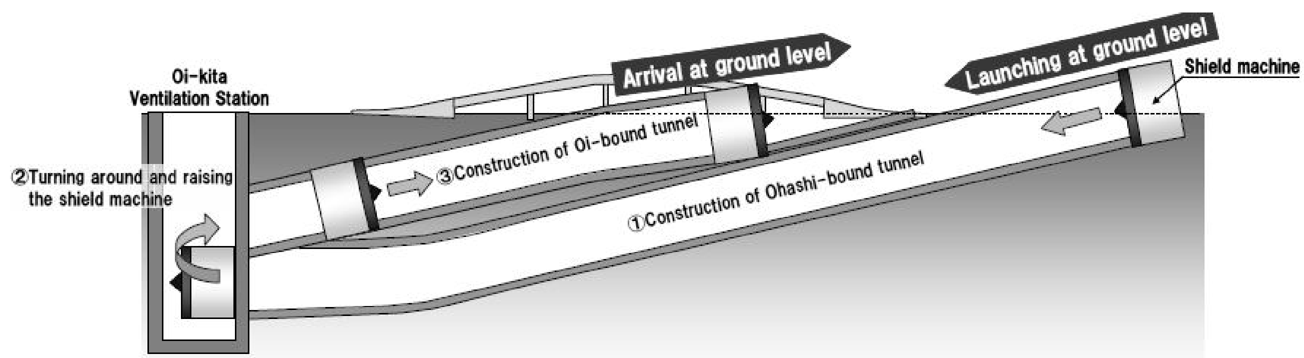

Figure 8. Tunnel construction sequence

The temporary steel members shall be installed horizontally in the tunnel cross section during the tunnel driving. The permanent structural beams shall be installed in the upper and lower parts of the tunnel cross section after the completion of shield tunneling, and then, the temporary steel members shall be removed.

c) Appropriate control of face pressure to prevent the deformation of surrounding ground

For the launching of shield machine at the ground level or driving under a shallow overburden, the face stabilization of shield machine is important to minimize deformation of ground. Insufficient or excess earth pressure in the chamber will affect the face stabilization. Therefore, the pressure in the chamber shall be properly monitored, and maintained and controlled appropriately. In the shield tunneling for the Oi Area Tunnel, the

pressure in the chamber to be maintained to equal to/or greater than assumed pressure, i.e. static earth pressure plus underground water pressure.
In ground-level launching, the plastic flow of excavated soil in the chamber can be directly observed visually. Therefore, proper quantity of additive and plasticity of the soil could be controlled with the visual monitoring the conditions of excavated soil in order to ensure safe and successful shield tunneling.
d) *Monitoring of adjacent existing structures*
In order to examine the impact of shield tunneling on these adjacent structures, advanced analyses have been carried out to examine the movement of and stresses in each structure. The analytical results indicate that there are no adverse effects on the adjacent structures. Trial measurement was conducted in the first 100-meter section where there is no adjacent structure. Settlement of the ground surface above the tunnels was measured to verify the effects of the face pressure control. The measurement results should be fed back to the analyses in order to minimize the impact of shield tunneling on adjacent structures. The results were able to be reflected in the tunneling control in order to ensure successful and safe tunneling work

3 LARGE SCALE REPAIR AND RENOVATION

3.1 *Planning*

To secure the safety of structures on the Metropolitan Expressway, meticulously inspection during day and night is carried out and repair works are implemented according to the results of inspections. As results of the inspection, critical damages due to aging, deterioration and harsh use are found as described 1.1.
The Metropolitan Expressway Co., Ltd. has taken on board the recommendations (January 15, 2013) made by the research committee tasked with reviewing approaches to large-scale renovation of Shutoko structures, and has deliberated over the expressway renewal plan (large scale renovation and large-scale repairs). On December 25, 2013, based on the above recommendations, careful investigation on the situations of problems and damages related to structures and the maintenance management efforts were carried out. As a result of investigating locations that should be renovated or repaired on a large scale, “The Metropolitan Expressway Renewal Plan (draft)” was established.

3.2 *Basic Policy for Renewal*

The followings are the basic policies establishing the renovation plan of Shutoko.

1) Ensure long-term durability
   Based on the latest technologies, application of technical standards, renovation plan and design should be carried out to ensure the long-term durability.
2) Ensure the maintenance of structure
   It is ensure the maintenance of structure by large-scale renovation, the adoption of structure of easy maintenance, installation of maintenance equipment.
3) Mitigate impact on the traffic
   The impact on traffic in the renovation work already in service road should be reduced.
4) Shortening construction periods
   For the early completion of renovation, the construction process should be shortened.
5) Reducing construction cost
   It is required to reduce the cost for renovation.
6) Strengthening of road function combined with renovation
   It is required to reduce congestion, improve driving safety and cooperate with urban redevelopment (Town Planning)

The sections where it is difficult to maintain management and large-scale renovation is efficient and effective are selected as large scale renovation section which is approximately 8km. The rebuilding of bridge and replacement of bridge slab will be carried out. Based on structural characteristics, the bridge spans on which damage has occurred are selected as large scale repair section that is approximately 55km. Those sections are shown in Figure 9.

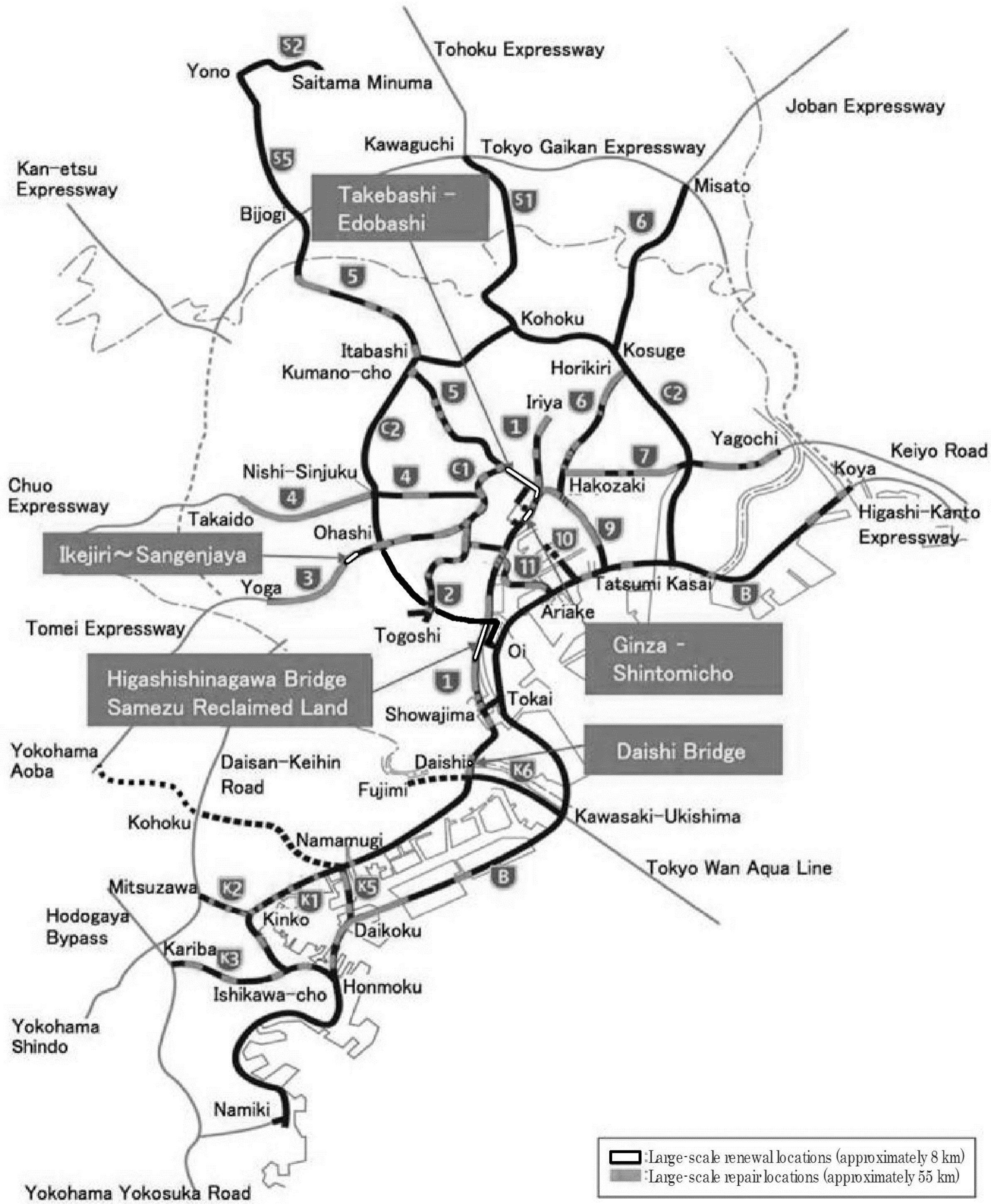

Figure 9. Renewal plan of the Metropolitan Expressway

3.3 *Example of Large Scale Renovation of Viaduct*

The section between Higashi-Shinagawa Bridge of Route No.1, Haneda Route and Samezu Landfill is introduced shown in Figure 9. This section was opened in 1963 for Tokyo Olympic Games. The superstructure of Higashi-Shinagawa Bridge is pier type reinforced concrete, and the foundation is prestressed concrete pile with the caisson for seismic force. Since Higashi-Shinagawa Bridge is built just above sea level, there exists very little space between the sea level and the bridge girders. Therefore, inspection and repair works are extremely difficult, and various damages such as spalling of concrete and corrosion of reinforcement by the corrosive environment, have been discovered as shown in Figure 10(a), (b).

Figure 10. (a), (b) Reinforced concrete girders extremely damaged by corrosive environment

On the other hand, the structure of Samezu Landfill area of Route No.1, Haneda Route, is a sort of temporary structure such as earth retaining wall with tie rod. Subsidence of road surface is occurred due to erosion of seawater. As a result of overall examination based on the basic policy for renovation, both sections of Route No.1, Haneda Route require large-scale renovation work due to their level of damage and to the fact that their structures are not suitable for long term service. Figure 11 and 12 shows the structures of this section before and after renovation.

Figure 11. Current situation (before renovation)

Figure 12. Viaduct after renovation

In order to construct structures away a certain distance from sea level, the entire pier type structures are removed. And in order to reduce the traffic impact during construction, a detour of expressway is constructed besides the existing expressway.

3.4 *Example of Large Scale Renewal of Bridge*

Expressway Daishi Bridge of Route No.1, Haneda Route is introduced shown in Figure 9. This bridge was opened in 1968. The superstructure of this bridge is 3 spans continuous steel box girder with orthotropic steel deck, the pier is reinforced concrete and the foundation is steel piles. The weight of superstructure is lighter since this bridge is designed by the old standards and has a longer span in order to minimize the impact on the Tama River. Therefore, fatigue cracks are easy to occur because the entire bridge is less rigidity. Although it is carried out repair of fatigue cracks, a large number of new fatigue cracks are occurred. In order to prevent occurrence of fatigue damage on the bridge, the entire bridge shall be replaced. For this reason, it is also necessary to replace the foundation since the load of the superstructure is increased. And in order to reduce the traffic impact during construction, a detour of expressway is constructed besides the existing expressway as well as 3.3.

Figure 13 shows re-occurrence of fatigue crack on the welding between the orthotropic steel deck and longitudinal rib from the tip of stop hole. Figure 14 shows the typical reinforcement of longitudinal ribs on orthotropic steel deck by splice plates.

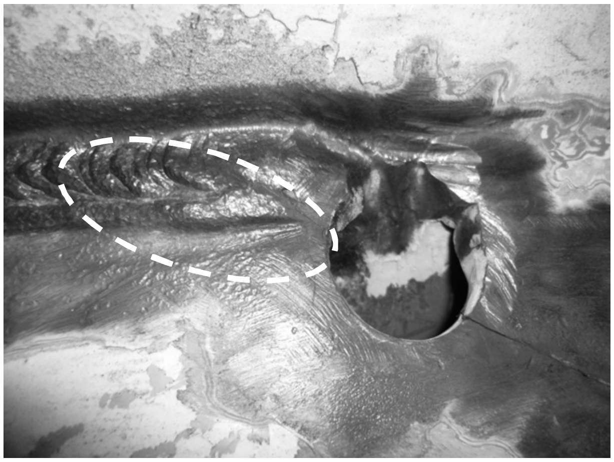

Figure 13. Re-occurrence of fatigue crack

Figure 14. Reinforcement of orthotropic steel deck

4 CONCLUSIONS

The operation of an effective traffic system requires a network with proper balance between radial and circular routes. Therefore, the development of the circular road plays an important role for the effective utilization of the rad network and securing the redundancy of the road system. However, circular routes in the Metropolitan Expressway network have not been developed to the extent that radial routes have, and the concentration of incoming traffic to the city center results in chronic traffic congestion. Consequently, construction of the Central Circular Route is urgently awaited as a fundamental means of improving traffic flow.

On the other hand, in high densely populated urban area such as Tokyo metropolitan, it is difficult to construct viaduct structures from the point of view of environmental preservation, ensuring the urban landscape and effective utilization of urban space. Therefore, the tunnel structure is employed for development of circular route. In order to reduce the impact on surrounding environment during construction, the proposed innovative construction method such as shield enlargement technology would be very effective.

After development of the infrastructure such as road, railway, subway and etc. the regular inspection should be carried out and as results of the inspection, appropriate repair works should be done. However, under the harsh use, deterioration and aging, critical damages are found. Based on the careful review and investigation described 4.2, large-scale renovation and repair of the structures are required to secure the safety and long term durability and to improve the maintenance.

The examples of large scale renovations introduced in this paper are the precedents of the Metropolitan Expressway. It will be expected to be a reference of the bridges in the same situation in the future.

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