4-1-1 Widening and underground bonding of shields using the largest scale freezing method in Japan for sewer construction

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1. ABSTRACT

The Senju District of Adachi Ward, Tokyo have been experienced flood caused by heavy rain frequent in recent years, as well as shortage of rainwater drainage capacity related to the increasing rainwater inflows to the sewers according to the rapid urbanization. Additionally, pump facilities constructed in the 1940s through 1960s have aged considerably. For these reasons, the Tokyo Metropolitan Government is proceeding in the Sumidagawa Sewer Trunk Line project which erect new rainwater trunk line and new pumping station to reduce flood damage, as well as to let us reconstruct the aged pumping stations.

The Sumidagawa Sewer Trunk Line is T-shaped. In this construction project, ground freezing was used as an auxiliary method to widen the shield tunnel underground to connect large trunk sewers of 6.5-meter external diameter to existing smaller trunk sewers of 5.5-meter external diameter. The amount of ground freezing was 3,700 m^3 and this was the largest-scale freezing project in the history of Japanese sewerage construction.

This paper describes the project's characteristics, including the process of freezing soil, the removal of pre-existing segments, the excavating of frozen soil, and the assembly of widening segments. It also reports on simulations and other initiatives conducted to achieve safe, efficient construction, and the use of Construction Information Modeling/Management, CIM.

KEYWORDS

Sewer trunk line, shield tunnel, ground freezing, removal of pre-existing segments, assembly of widening segments, CIM

2. INTRODUCTION & BACKGROUND

Tokyo can be divided broadly into two areas: the 23 wards in the east and the Tama area in the west. The total length of sewage pipes in the 23 wards is 16,000 km of sewage pipes, which could extend from Tokyo to Sidney and back again. There are twenty sewage treatment plants in Tokyo and treat 5.56 million m^3 of sewage every day (Fig.1).

Fig.1 Map of Metropolitan Tokyo

The Senju District of Adachi Ward, Tokyo has been suffered flood damage several times in the period from 1991 to 2008. In the high economic growth period in Japan, sewerage system was constructed to remove 50% of an assumed 50 mm of rainwater per hour. It was because there were still fields and green spaces in Tokyo in this period that would absorb half of the rainwater into the soil, and thus it was thought that half would be treated by sewage pipes (Fig.2).

Fig.2 flood damage in the Senju District of Adachi Ward

As the rapid urbanization, most of the land had been covered in buildings, concrete, and asphalt. There was less soil to absorb rainwater, and more water flowed into the sewer system. In fact, the amount of rainwater flowing into the sewerage grew to 1.6 times what it had been in the early-mid twentieth century when sewerage construction began. This inflow into sewage pipes exceeded the design capacity of the pipes and caused the flood. Therefore, Tokyo Metropolitan Government (TMG) is improving sewerage facilities to be able to remove 80% of an assumed 50 mm of rainwater per hour (Fig.3).

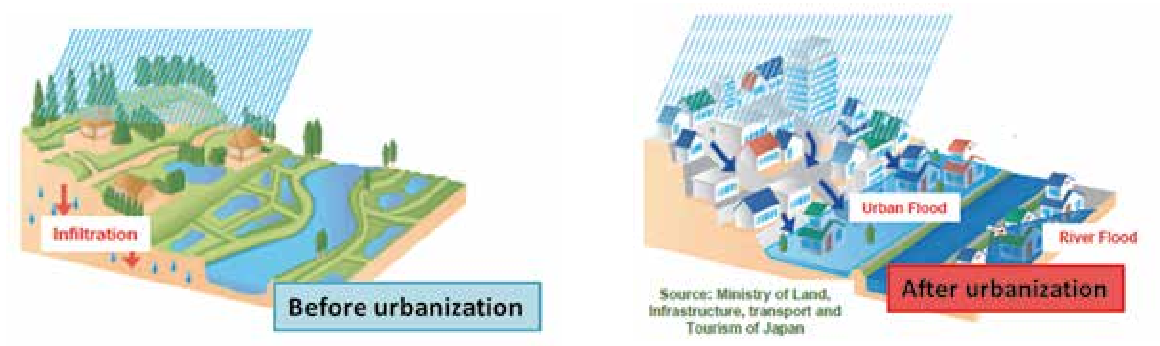


Fig.3 Difference of absorbing rainwater

TMG designated the Senju District of Adachi Ward as one of the priority area for improvements aimed at reducing flood damage. To this end, TMG has launched the Sumidagawa Sewer Trunk Line construction project. This project contains the construction of rainwater collection pipes (i.e. the Sumidagawa Sewer Trunk Line) that will capture rainfall in 292.85 ha of the 410.7 ha total surface area of the Senju district and also involves the construction of pumping station to discharge rainwater into rivers.

In the first phase of the Sumidagawa Sewer Trunk Line construction project, a 3.11-km long shield tunnel was built of external diameter of 5.5 m and internal diameter of 4.75 m. Next, a shield tunnel with an external diameter 6.35 m and an internal diameter of 5.5 m would be connected from the side of pumping station construction site. In order to connect the larger shield with a 6.35 m external diameter to the smaller shield with a 5.5 m external diameter, it was necessary to widen the existing tunnel (with the smaller connecting external diameter) underground. Ground freezing was employed as an auxiliary method in the widening of the shield tunnel. This project produced 3,700 m^3 of frozen soil, making it the largest-scale ground freezing project in the history of Japanese sewerage construction (Fig.4).

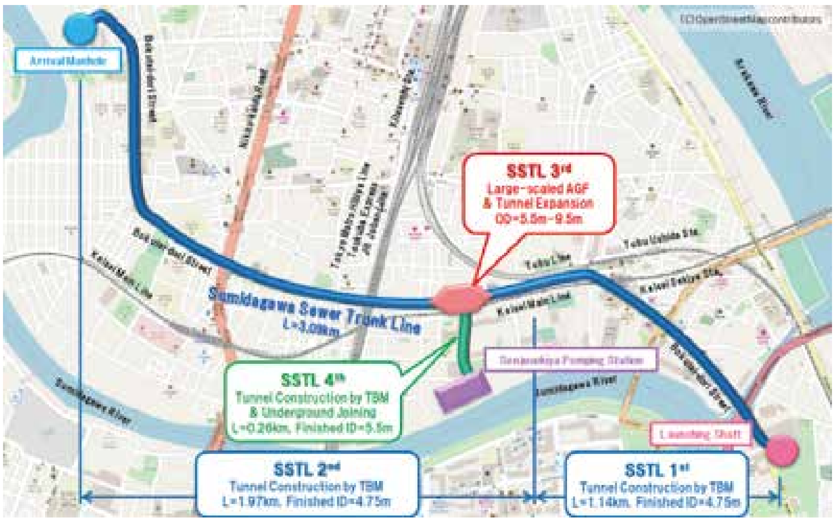


Fig.4 The Sumidagawa Sewer Trunk Line

The soil where be frozen and thawed in this project was mainly composed with cohesive soil. There could be a large amount of both frost heaving and subsidence during the freezing and thawing phases, respectively.

From the next section, background behind the selection of the ground freezing process, the phases of the construction project, and the key features of the project will be described.

3. SELECTION OF THE GROUND FREEZING PROCESS

The condition of this project was under the following circumstances (Fig.5).

(1) There were high-traffic major roads, as well as train tracks above the section to be widened.

(2) There were a lot of underground pipes such as sewage pipe, water pipe, gas pipe and electrical lines.

(3) The section to be widened was at a great depth of around 40 meters and under the high water pressure.

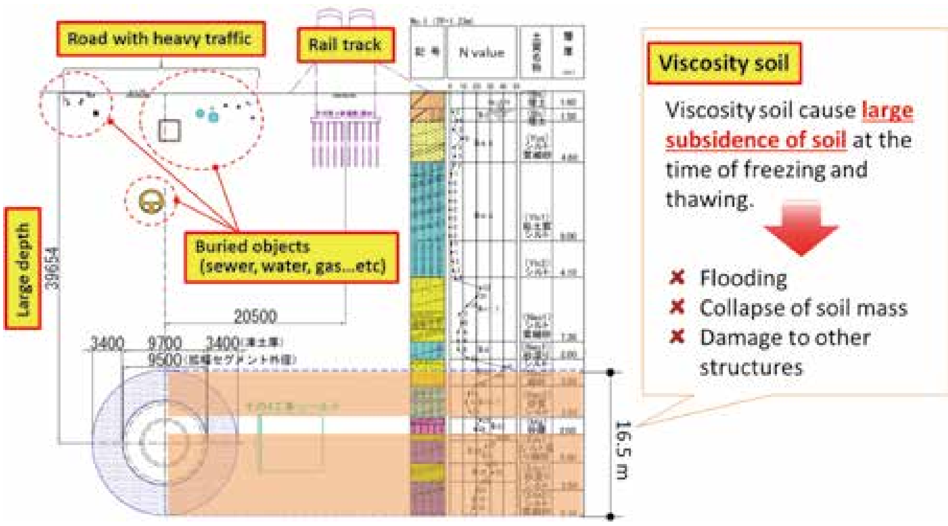


Fig.5 Cross section/soil column diagram

When connecting sewage pipes underground, usually shaft is to be built considering the workability and maintenance. However, it was very hard to build a shaft under the circumstances mentioned above. There was also a risk that building a deep shaft would have any impacts on train tack.
For these reasons, it was decided that widening without digging was adopted in this project. Ground improvement method was crucial to preventing collapse and groundwater leaking into the tunnel. However it was predicted to be difficult to drill and inject from the ground due to the site's circumstance and underground utilities. Moreover, it was expected that there would be unimproved soil left underneath the existing pipes. Therefore, it was decided that ground improvement work would not be performed from above ground.
According to the result of soil surveys, target layer was composed silty and an N value is above 20. That was difficult to improve the soil condition precisely by inner method. Meanwhile, the ground freezing method would uniformly improve the full area, sealing off water and securing the necessary

soil strength even though it is more expensive than inner method. For safty reasons, the ground freezing method was chosen for this project.

4. PHASES OF CONSTRUCTION

Followings are the flow of underground connection in this project.

- First, freezing pipes were inserted in a radial pattern from inside the shield tunnel as shown in Fig.6. 186 such freezing pipes were inserted using a tunnel boring machine.

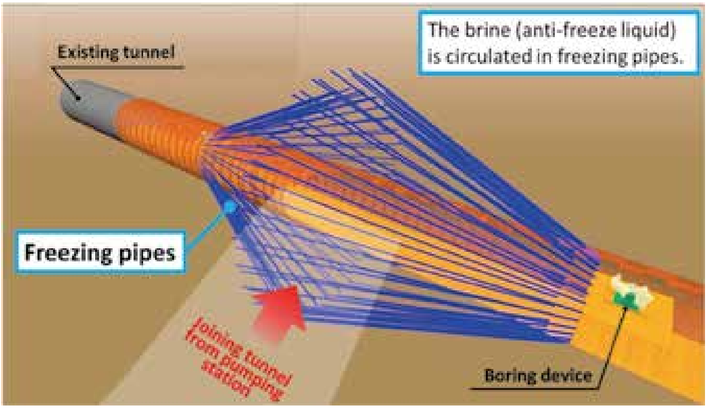


Fig.6 Freezing pipes

- Next, pipes were inserted as shown in Fig.7 by the yellow line to measure the temperature of the frozen soil. 32 such pipes were installed for temperature measurement.

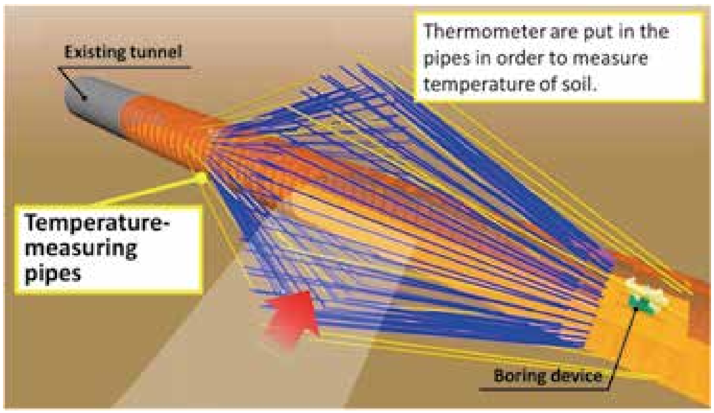


Fig.7 Temperature measuring pipes

- Interior freezing pipes were inserted as shown in Fig.8 to ensure that the frozen soil would not collapse while the segment widening work was in progress. 58 such pipes were installed.

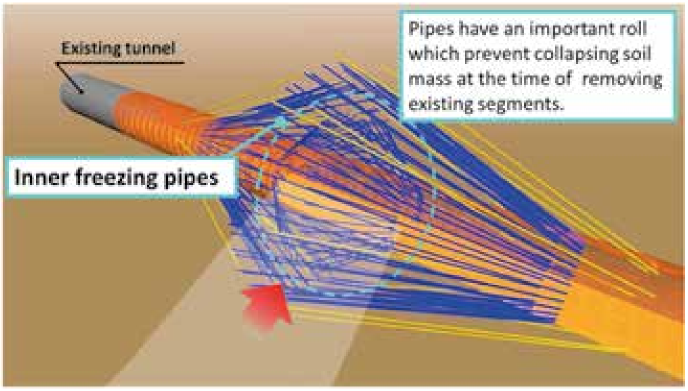


Fig.8 Inner freezing pipes

- 704 wall-attached freezing pipes were inserted to prevent the leakage of groundwater into segments. The Fig.9 shows actual wall-attached freezing pipes used in this project.

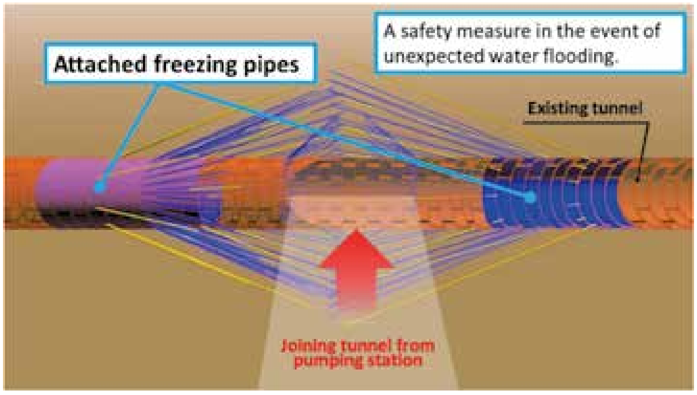


Fig.9 Attached freezing pipes

- An -30-degree antifreeze was circulated through the freezing pipes to gradually freeze the soil and ultimately created frozen soil of thickness 3.4 m (Fig.10). The process of freezing the soil required 5-6 months to produce 3,700 m^3 of frozen soil. Fig.11 is a photo of the interior of a segment during freezing.

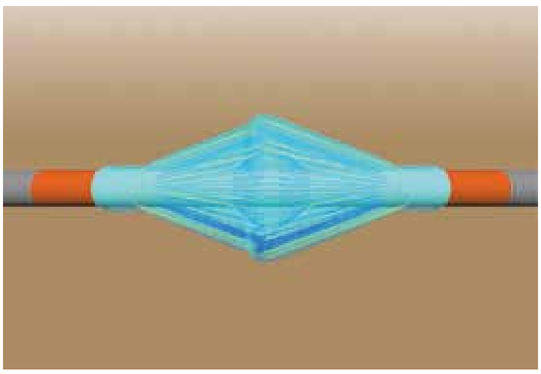


Fig.10 Ground freezing

Fig.11 Inside the pipe in freezing

- After the soil was successfully frozen, the pre-existing segments were removed, the frozen soil dug out, and gradation segments assembled. Fig.12 shows the exposed frozen soil with the pre-existing segments removed, and the Fig.13 shows the frozen soil being dug out.

Fig.12 Frozen soil drilling

Fig.13 Segment assembling

- After several repetitions of the process of removing pre-existing 5.5-m external diameter segments, digging out frozen soil, and assembling the widened segments with a maximum external diameter of 9.5 m, the segment-widening work was complete (Fig.14).

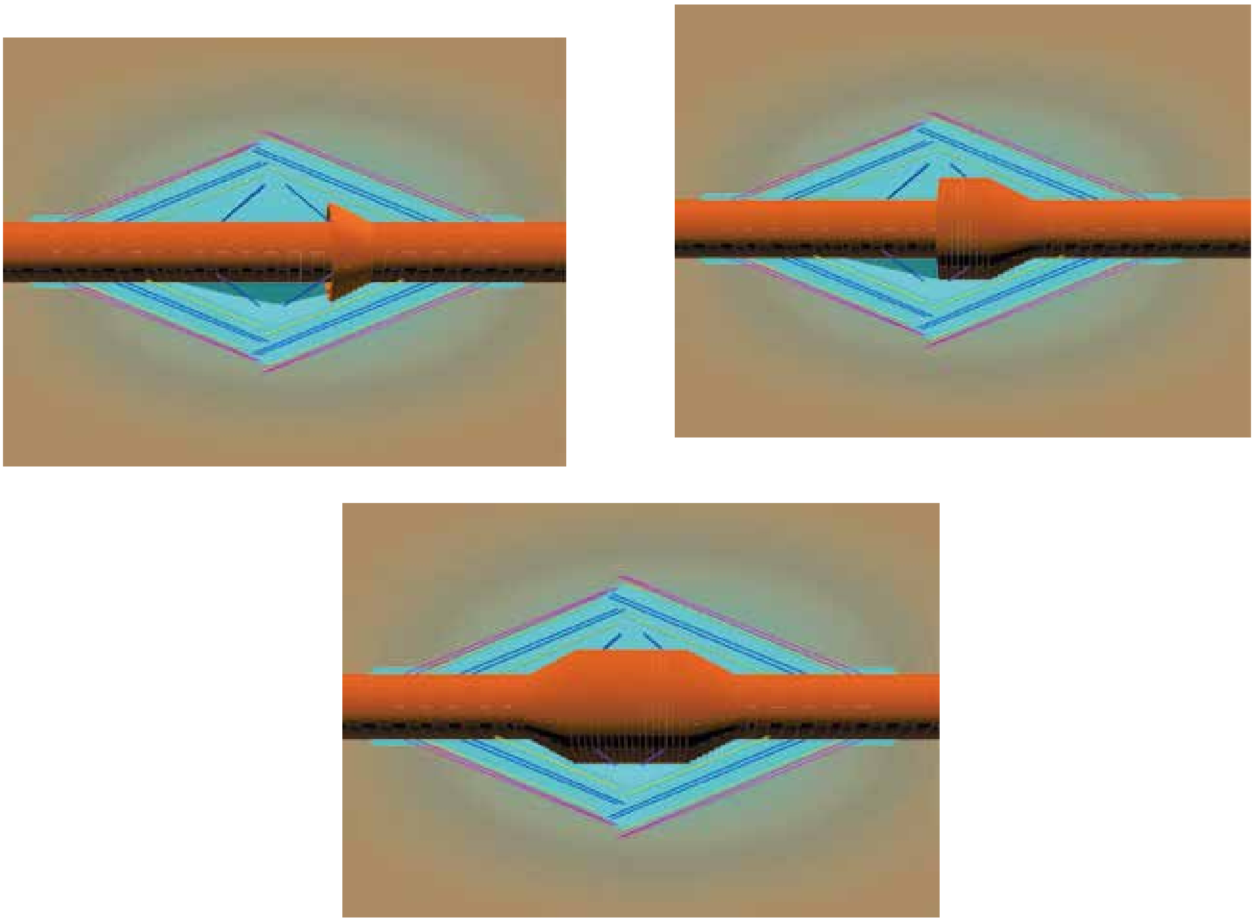
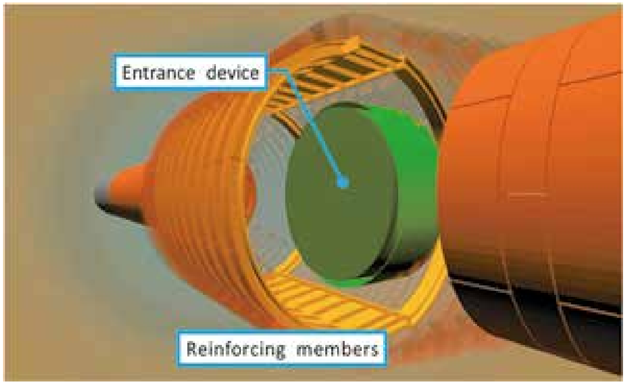


Fig.14 Flow of expanding the segments

- A receiving mechanism was installed for the shield that would establish the underground connection (Fig.15).



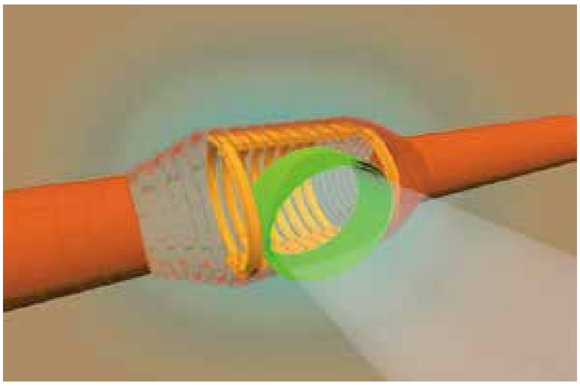


Fig.15 Entrance device

- 60-degree warm water was then circulated through the frozen pipes to thaw the frozen soil (Fig.16). To help control subsidence in the surrounding area, cement-bentonite grouting was conducted. Once subsidence stabilized in the segments and surrounding structures, the forced thawing and cement-bentonite grouting were complete.

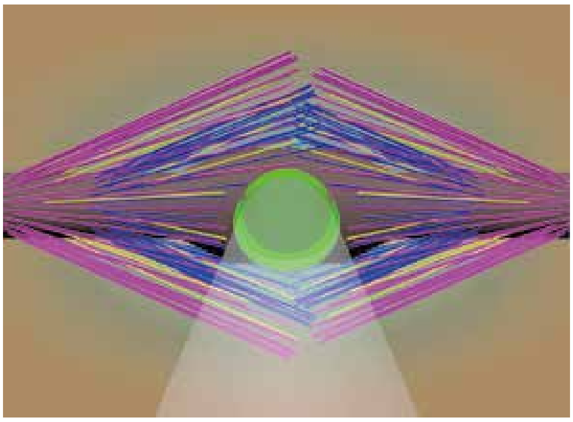


Fig.16 Forced thawing

- Finally, the shield machine with an external diameter of 6.5 m was connected in a T shape. Once the shield machine reached to the extended segments, the section between the entrance and the shield machine was sealed off to water. Next, the lid of the entrance as well as the faceplate and partition of the shield machine were removed to complete the connection (Fig.17). These were the flow of underground connection in this project.

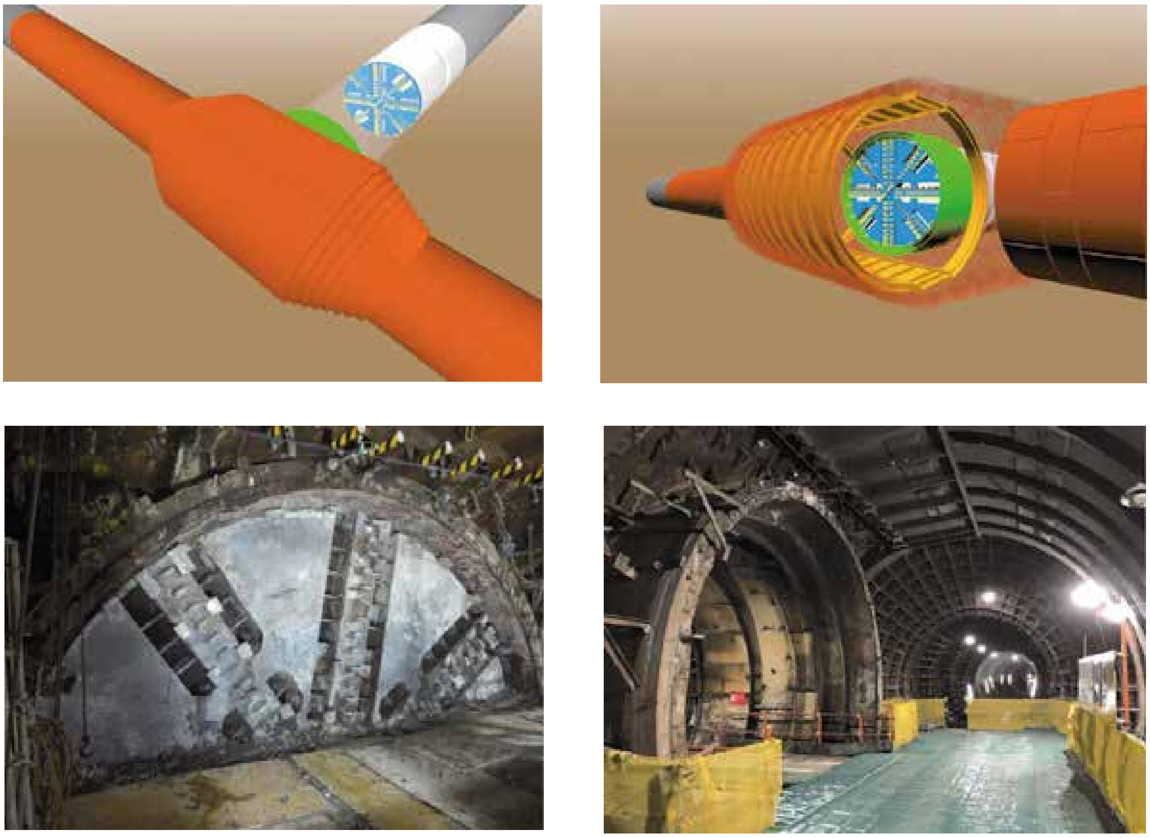


Fig.17 Shield machine connecting

5. KEY FEATURES OF THE PROJECT

The next section will describe the key features of this project.

5.1 GROUND FREEZING

In the ground freezing phase, casing pipes were dug radially from the segments of external diameter 5.5 m and 186 interior freezing pipes and 32 temperature measurement pipes were installed. In addition, 704 wall-attached freezing pipes were attached to improve the strength of the attachment of the frozen soil to the segments and prevent the leakage of groundwater into segments. The process of freezing the soil required 5-6 months to produce 3,700 m^3 of frozen soil, making this the largest-scale ground freezing project in the history of Japanese sewerage construction.

Furthermore, 128 of radial thawing pipes were installed around the frozen soil to help control the impact on rail and nearby structures. This technique was first experiment in Japan and succeeded in limiting frost heaving to just 8 mm (Fig.18).

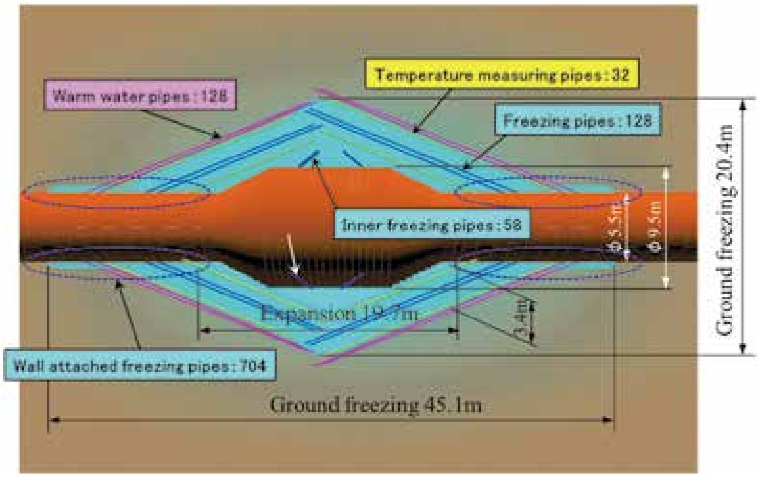


Fig.18 pipes using for ground freezing

5.2 FROZEN SOIL EXCAVATING AND SHIELD TUNNEL WIDENING

Shield tunnel widening under high water pressure and frozen soil condition was the first attempt in Japan. The external diameter was widened 4 meters, from 5.5 m to 9.5 m. Therefore, in order to minimize open surfaces on the frozen soil and prevent soil collapse and groundwater leakage, segments were given a gradated structure in which the shield connection parts had an external diameter of 9.5 m, and both sides of this 3.5-meter span changed external diameter gradually in 0.5-meter increments. Thus, all segment widths were made 0.5 meters (Fig.19).

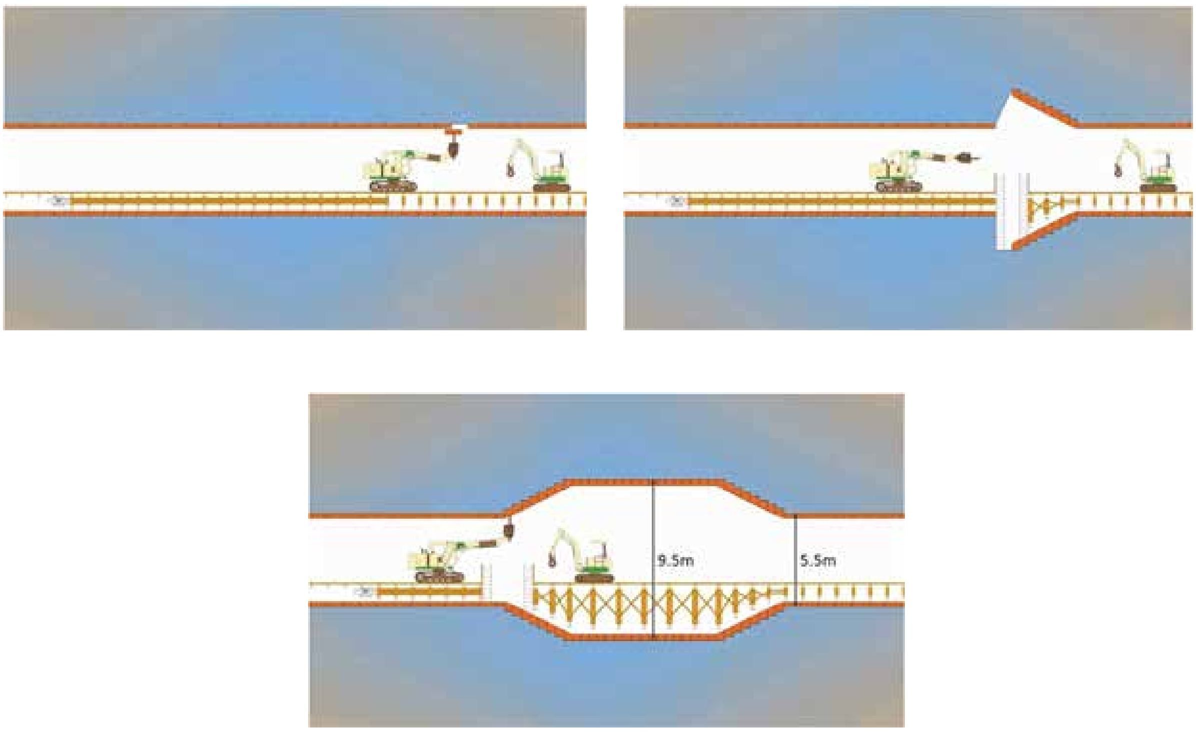


Fig.19 Shield tunnel widening

5.2.1 SELECTION OF A EXCAVATION MACHINE FOR FROZEN SOIL

An above-ground test run of a tunnel boring machine for frozen soil was conducted as shown in Fig.20 to check the machine's performance, suitable cutting attachments and bit shapes. These tests led that twin rotating head was better than single rotating head and rotating head tip used for asphalt was more efficient to dig for this project (Fig.20).

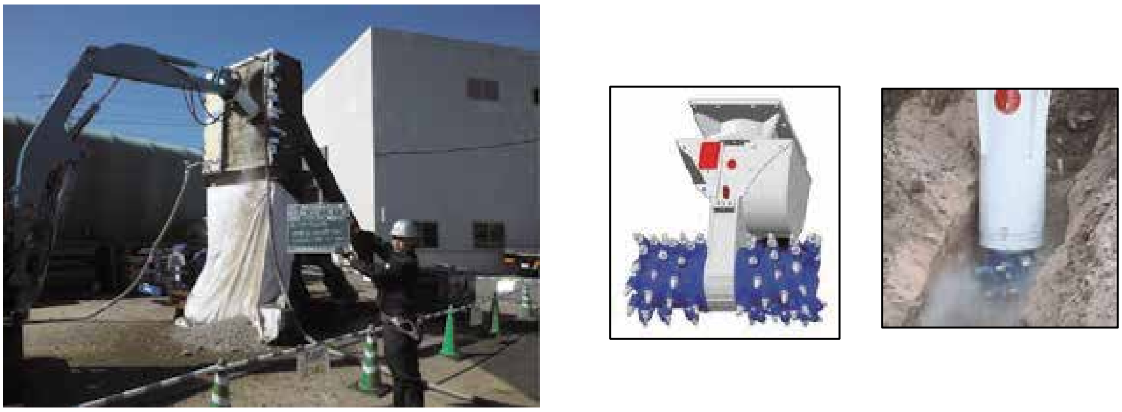


Fig.20 Test run of frozen soil excavation machine and cutting attachment

5.2.2 SEGMENT ASSEMBLY MACHINE

Special attachments for holding segments were set up for steel materials handling machine. Mock cross-sections were created above ground for simulation and testing purposes. The testing involved the above-ground removing of a pre-existing segment and the assembly of a widened segment was conducted in advance to investigate aspects including the restrictions on handling machine movements inside the restricted space of a pre-existing segment (Fig.21).

Fig.21 Experiment of segment handling machine

5.3 FORCED THAWING

In general, it takes approximately a year and eight month to thaw naturally 3,700 m^3 frozen soil. Therefore, 60-degree warm water was circulated through the pipes in the frozen soil to force thawing for the purpose of shortening the length of the project while still maintaining safe conditions.
During this process, cement-bentonite grouting was conducted to prevent any subsidence that might occur during thawing. A grouting simulation was conducted before the actual thawing phase to determine the quantity of cement-bentonite required. Segment displacement was monitored and grouting was conducted intensively where major displacement was exhibited. These efforts helped minimize the impact of the thawing on the surrounding environment and ground subsidence amount was just 8 mm, which was less than the 11 mm that was predicted (Fig.22).
It's been approximately 5 month to thaw owing to this forced thawing which is significantly shorten the period.

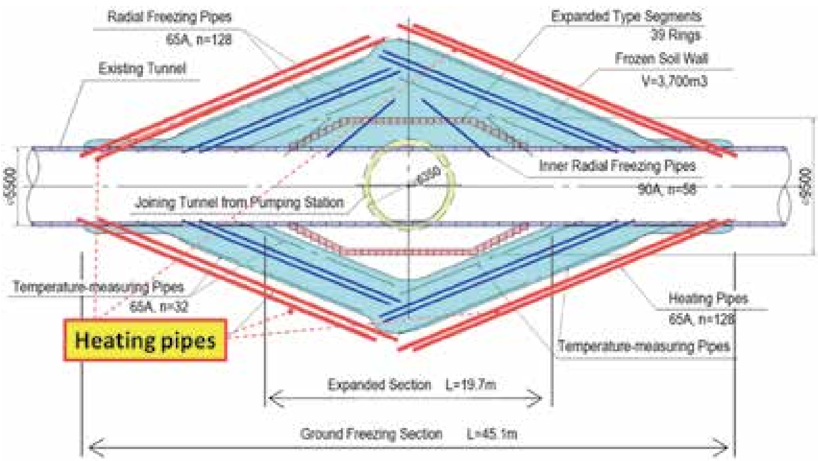


Fig.22 Forced thawing

5.4 USING A CONSTRUCTION INFORMATION MODELING/MANAGEMENT

CIM is an acronym for "Construction Information Modeling/Management", an initiative announced by the Ministry of Land, Infrastructure, Transport and Tourism in 2016. It aims to improve the efficiency and sophistication of a series of construction project by introducing 3D models from the survey design stage and linking to 3D models in the construction stage.
In this project, three types of 3D models were developed and utilized for construction management to resolve various issues in the ground freezing and segment widening process.

5.4.1 USING A CIM FOR GROUND FREEZING STATUS CHECK

In the ground freezing process, it is essential that the soil certainly be infilled and to be strong. In addition, it is necessary to accurately know the positioning of underground freezing pipes and adjust the positioning of following pipes. It is also necessary in the ground-freezing process to successively predict the thickness of walls of frozen soil and the status of obstruction. In the past, such construction processes were managed using two-dimensional tools and methods as shown in Fig.23. However, it was not possible to monitor the positions of underground freezing pipes or frozen soil formations.

In this project, therefore, 3D model as shown in Fig.24 was used for progress monitoring from the freezing pipe installation phase. Using this 3D model, the positioning of following pipes were adjusted to ensure the ground was certainty frozen over the planned area. Additionally, a system was developed and implemented that would periodically display in a 3D space the process by which columns of frozen soil gradually widened. This system enabled up-to-date monitoring of information such as the extent to which columns of frozen soil had grown and where void still remained.

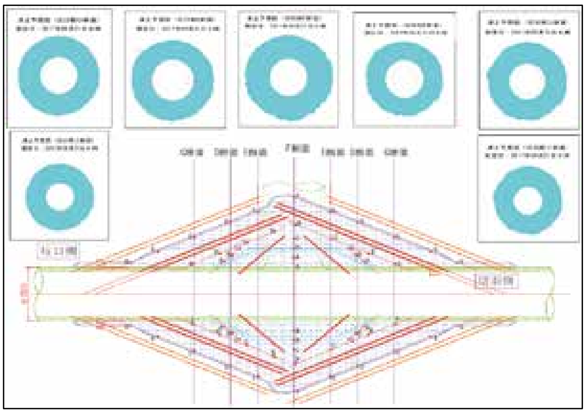


Fig.23 Frozen soil creation status check (conventional method)

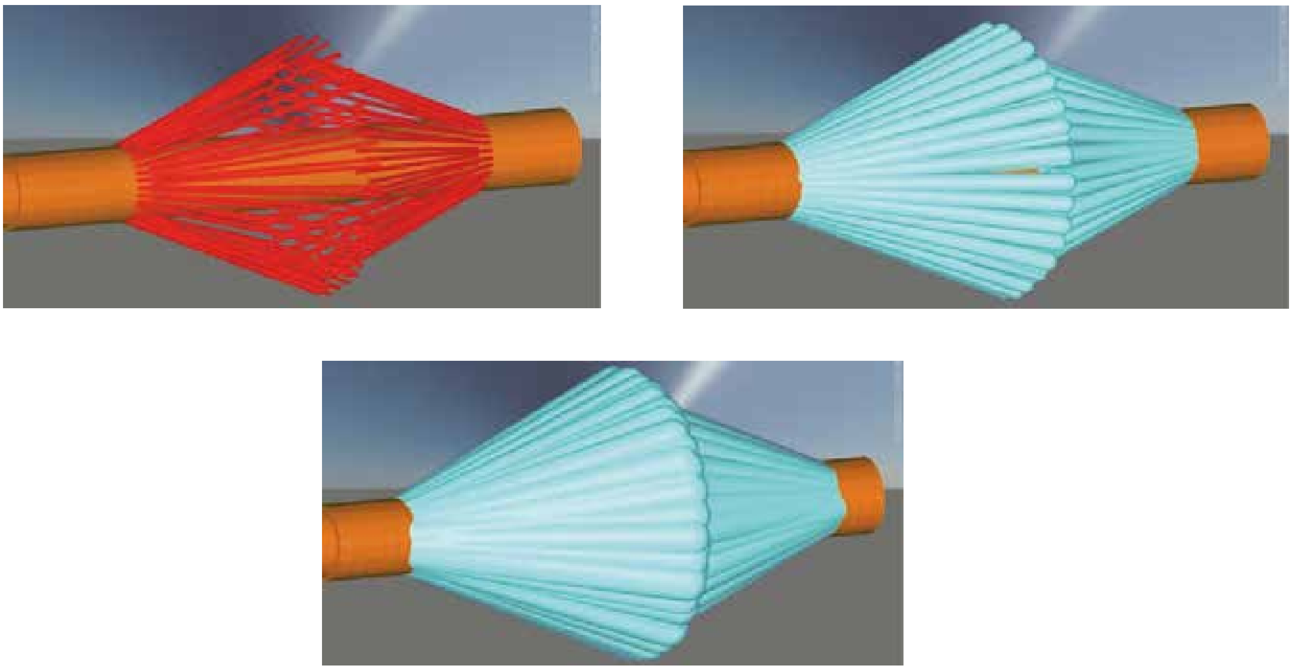


Fig.24 Frozen soil creation status check using CIM

5.4.2 DEVELOPMENT OF A HEAVY EQUIPMENT SIMULATORS

The widening work in this project it was needed that segment removal and assembly work had to be done in narrow space (interior diameter of 4.95 m and a length of 19.7 m) congested with freezing-related equipment. Therefore, it was necessary to study in detail how to place and operate each piece of heavy machinery for the best efficiency and safety. However, this was difficult to analyze using the conventional two-dimensional diagrams. To address this need, this project included the development of heavy equipment simulators for widening work that combined a 3D model of a simulated tunnel interior with a heavy equipment model operable using a gauge on a PC screen. These tools enabled a theoretical simulation based on the actual conditions inside a tunnel and the in-depth examination of the finer movements of heavy equipment that conventionally needed to be checked and handled on the spot (Fig.25).

Fig.25 Simulatiors of segment removal and assembly

5.4.3 CENTRALIZED MANAGEMENT OF MEASUREMENT DATA USING 3D MODELS

In this project, there was the possibility that ground freezing or widening work would cause uplift or subsidence and would affect above-ground railway structures, roads and underground pipes. Therefore, various types of measuring instruments were installed in over 1,500 spots above ground, underground and in tunnels to monitor measurement data during the construction. If this massive quantity of measurement data were individually graphed out and displayed on multiple monitors as per conventional methods, it would be impossible to observe all changes and measured positions at once. In the past, this led to delayed decision-making. To address this, this project developed a 3D model to centrally manage all measurement data on a single screen, matching graphical elements with actual measured positions in a 3D model space and using changes in color to reflect the values of measurement data (Fig.26). Thanks to this 3D model, checking measured data have become easily by displaying converted positional information. The use of these 3D models to monitor the construction minimized the impact of the work on the surrounding environment and enabled difficult work to be carried out safely and precisely.

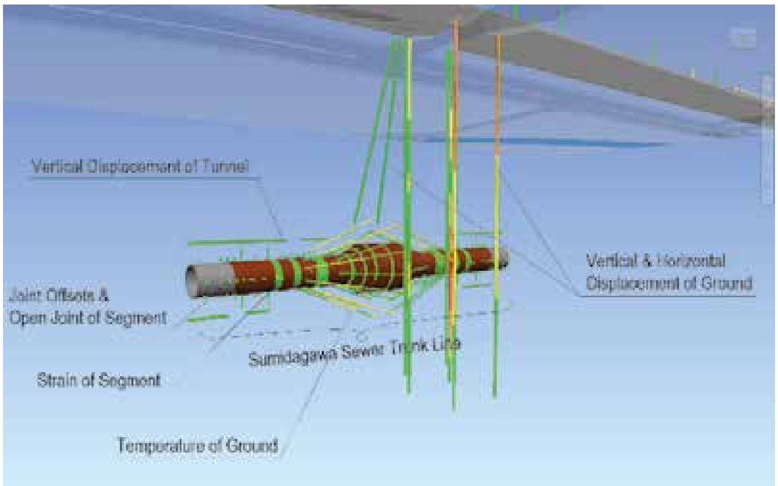


Fig.26 Centralized management of multi-point measurement values using CIM

6. CONCLUSION

The construction condition of this project was characterized as very difficult due to a lot of adjacent structures such as above-ground railway structures or roads, or damage underground pipes and under high water pressure of 40 meters underground. Regardless, the project was successful in widening a shield tunnel using the largest-scale ground freezing in the history of Japanese sewerage construction and establishing an underground connection with a final precision of 10 mm, without any accidents or damages.

In urban areas with a high volume of traffic and overcrowding among underground utilities, it is inevitable that underground structure construction will need to be conducted at a great depth and without open excavation. Depending on the specific restraints and parameters of the construction project, there may be cases in which a small tunnel must first be constructed before a larger tunnel is created for underground connection. In some of those cases, ground freezing may be selected as one auxiliary option. It is hoped that the findings of this project regarding ground freezing and thawing work can be of service to similar construction projects in the future.

7. AKNOWLEDGEMENT

We appreciate all the people of the contractor, who were devoted to the investigation, planning and the construction of this project.

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