Flood Control Trunk Sewer Line Project Featuring the World’s First Double Shield 90 Degrees Rotation

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1. ABSTRACT

Tokyo Metropolitan area suffers flood damages because of the insufficiency of rainwater drainage capacity, which cannot keep up with the increase of rainwater inflow caused by urbanization and localized heavy rain which is occurring frequently in recent years. This project is to construct “Tachiaigawa Trunk Sewer Stormwater Outlet Channel” as a measure against flooding in the Tachiai River basin in Shinagawa-ku, one of the Facility Improvements for Handling 50 mm/h Rainfall intensity (anti-inundation project promotion areas) based on “Basic Policy on Measures for Torrential Rain (Revised),” and also to discharge the stormwater, which is currently released to the Tachiai River, to the Keihin Canal in order to improve the water quality of Tachiai River/ Katsushima Canal as one of the measures to improve the combined sewer system.

We will report issues and measures in the world’s first spiral excavation in H & V shield method, which was adopted to construct the Tachiaigawa Trunk Sewer Stormwater Outlet Channel in this paper.

KEYWORDS
Anti-inundation trunk sewer, shielded tunnel, H&V shield method, spiral excavation, under narrow River

2. INTRODUCTION & BACKGROUND

Tokyo can be coarsely classified into 23 Wards and Tama Area. The sewer pipes managed by Bureau of Sewerage is so long that the total length of the pipes in the Ward area reaches 16,000 km, which is comparable to the return distance between Tokyo and Sidney. Additionally, the “Water Reclamation Centers” (Sewage Treatment Plants), which are located in 20 places in 23 Wards and Tama, are processing 5.56 million m³ of sewage every day, which is comparable to the 4.5 times as much as the capacity of Tokyo Dome.

Heavy rains exceeding 50 mm/hour are increasing in Tokyo these days and therefore the Bureau of Sewerage is improving the sewage facilities so that they can cope with rainfalls of 50 mm/hour in the overall Ward area, aiming at preventing floods, based on “Basic Policy on Measures for Torrential Rain (Revised)”.
The neighborhood of Higashi-oi area, Shinagawa Ward, where the project is executed, is one of the Facility Improvements for Handling 50 mm/h Rainfall project promotion areas. It is located in the south of Tokyo Metropolitan area, with southern part close to Tokyo Bay and Haneda Airport; it is one of the most highly populated areas in Tokyo and numerous projects such as the construction of large-scale terminal station, Shinkansen, main roads, high-rise buildings, and urban renewal projects are executed. With the above background, this area requires construction projects including sewer pipes construction to consider numerous effects to the neighborhood; this is the place which requires advanced management.

Table 1: Outline of the Construction

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Image 1: The deterioration of water quality in the Tachiai River
(Left: normal state Right: deteriorated water quality state)

The Tachiai River flowing in the district is a “class B” river (Small River) with the length of 7.4 km, whose lower 750 meter section of the river is open ditch, and the upper section is closed as a trunk sewer (Tachiaigawa Trunk Sewer). Tachiaigawa Trunk Sewer was constructed into a culvert during 1969 - 79. Since this trunk sewer, which has been covered with a lid, was originally a river, its earth covering is rather shallow and apt to bring about floods, anti-
inundation work is executed in various points. Additionally, the water quality of Tachiai River and Katsushima Canal connected to its lower segment is degraded because of the river flood frequently occurring these days and stormwater mixed with sewage overflowing above the weir between the covered and open segment of Tachiai River.

Image 2: Flooded state of Tachiai River (Left: normal state Right: flooding state)

This project is to construct “Tachiaigawa Trunk Sewer Stormwater Outlet Channel”(Table 1) as a measure against flooding in the Tachiai River basin in Shinagawa Ward, one of the Facility Improvements for Handling 50 mm/h Rainfall (anti-inundation project promotion areas) based on “Basic Policy on Measures for Torrential Rain (Revised),” and also to discharge the stormwater, which is currently released to the Tachiai River, to the Keihin Canal in order to improve the water quality of Tachiai River/ Katsushima Canal as one of the measures to improve the combined sewer system.

Figure 1: Tachiai River Trunk Sewer Stormwater Outlet Channel surroundings diagram
3. HISTORY OF THE DISCUSSION LEADING TO THE ADOPTION OF H & V SHIELD METHOD AND SPIRAL EXCAVATION, AND THE OUTLINE OF THE METHODS

 Originally, it was planned that Tachiaigawa Trunk Sewer Stormwater Outlet Channel was to be constructed under the Tachiiai River, which is 8 meter wide. However, based on the subsequent negotiation with stakeholders and hydraulic model study, it was revealed that ordinary circular pipes could not secure sectional-area sufficient for the required flowability and that the bank protection pile in the neighborhood of the start shaft would obstruct the course. Constraints to be overcome in order to repair the Tachiaigawa Trunk Sewer Stormwater Outlet Channel were as follows:

 (1) Lower Limit Imposed by the Requirement of Securing Flowability
 Since the sewage flows within pipes by gravity, Tachiaigawa Trunk Sewer Stormwater Outlet Channel, which is constructed in this project, had to be higher than the bottom of the downstream pipe in order to secure flowability (Figure 3).

 (2) Upper Limit Imposed by the Bank Protection Pile
 The starting vertical shaft faces the canal and there is a bank protection pile on the boundary between the shaft and the canal. The height of the pipe bottom was set considering the lower limit described above, and consequently it has turned out that upper part of the tunnel would obstacle the bank protection pile if it was constructed along with the initial plan (Figure 3). Therefore, the upper part had to be made lower than the lower end of the bank protection pile to allocate a certain amount of spacing between them.

 (3) Limit on the Both Sides Imposed by the River Width and the Public-Private Boundary
 Since it was difficult to allocate routes around the construction site because of the convergence of underground installations, etc., it was necessary to construct the pipe under the Tachiiai River. Because the Tachiiai River has a narrowing place on the way and adjacent private property must not be influenced by the sewer pipe, the facility had to be contained within the width of the river, 8 meter.

 Hence H & V shield method was evaluated as a solution to clear the upper, lower, left, and right constraints.
Each constraint was cleared by excavating the sewer pipe not in the ordinary single shield method but in twin shield. The upper and limit were cleared by starting the two shields side by side, and the constraint on the width was cleared by twisting the excavation lines on the way; the twin tunnel becomes tandem to fit within the width limit of 8 meter.

H & V shield method, which enables structuring a spiral twin tunnel, was adopted; two shield machines with the diameter 5.85 meter each start excavating simultaneously, extremely adjacent to each other (with the gap of 90 mm), and the shield machines proceed rotating by 90 degrees after passing below the existing bank protection pile to form a twisted tunnel (Image 3).
Mechanism of the spiral excavation is to operate the buckling device of the machine on the right-hand side to increase the reaction force to the shield machine, thereby obtaining the rotating force (spiral force) from the force of elevating the right machine (warping effect); then the whole shield machine is rolled (Figure 4).

Figure 4: Mechanism of the spiral excavation

Right tunnel:
Composite curve with planar and longitudinal curve Three-dimensional curvature radius R 1290 m

Figure 5: Spiral linearity (Blue: left tunnel Red: right tunnel)

Image 4: H & V shield machine installation completed (The starting vertical shaft)
Figure 6: Positional relationship between revetment pile and shield machine on the starting vertical shaft side

H & V shield machines are started in parallel and the tunnel enters the spiral segment after excavating about 40 meter. Then the right-hand machine goes spiraling around the left-hand tunnel by 90 degrees (0.65 degrees/m) during the spiral segment of about 137.4 meter (Figure 6).

4. CONSTRUCTION ISSUES OF THE SPIRAL EXCAVATION

(1) Reliable Construction of the world’s first Spiral Excavation
There have been 5 constructions done by H & V shield method; this work is the 6th. Only one construction, as a demonstration test, has been done in the spiral excavation. The outer diameter in the construction was 2.12 meter and the spiral excavation method was TYPE-A. On the other hand, this project constructs two pipelines with each outer diameter 5.85 meter simultaneously with a slurry type H & V shield machine, and the spiraling method is TYPE-B, without any precedent. Since TYPE-B, in which twin tunnels are excavated with one tunnel spiraling around another, has no past track record, various predictions of the situation and careful management are required.

Figure 7: Spiral pattern of H & V shield construction method
(2) **Issues Caused by Rigid Connecting Joint on the rear body part**

Because usually, H & V shield machines have their rear body fixed, the direction of the rear body might not be aligned to the tunnel curve if the body is adjusted only by buckling the front body. Therefore, the tail clearance is reduced, and consequently the overbreak amount becomes large, making the neighborhood ground apt to be influenced (Figure 8). Additionally, the machine is required to excavate in a spiral with exclusively the warping effect of the front body by buckling operation, requiring a large ground reaction.

![Diagram of front and rear body with rigid connecting joint](image)

**Figure 8:** The Mismatch between the direction of the rear body and the shape of the curve

(3) **Issues Caused by the Eccentricity of the Shield Jacks**

While excavating in a spiral, front and back of the jack move eccentrically and consequently unsymmetrical force is generated in the thrust force of the jack, thereby causing aperture or deformation in the segment.

(4) **Suppressing Ground Deformation**

According to the previous analysis, overbreak outside the shield machine becomes as much as 350 mm at most during the spiral excavation. Hence it is expected that ground movement influences on the river structure and neighborhood.

(5) **Maintaining Ground Reaction Force and Precise Management of the Curve Shape**

Since the tunnel is aligned in a three-dimensional curve, highly accurate management of curve shape is required. However, since the outbreak amount is as large as 350 mm, large ground reaction force might not be obtained; the segment might be displaced or deformed by jack thrust, thereby making the tunnel curve out of the planned course.

Because H & V shield has twin-body structure, both “outbreak amount” and “tail clearance” of the two machines must be monitored simultaneously. Since the curve shape is quite complicated in the spiral section, it becomes very difficult to check these two amounts and rub might occur in the tail part, making appropriate curve shape management impossible.
5. MEASURES IN THE CONSTRUCTION PLAN

(1) Prior Understanding of Control Method for Shield Machine using H & V Shield Simulator
Interaction among the excavating shield machine, ground, and segment were analyzed with an H & V shield simulator applying the shield machine dynamic model. Appropriate jack pattern, outbreak amount, and buckling angle, etc., which were reflected to the shield excavation plan, were identified by utilizing the simulator. Additionally, an excavation management console corresponding to the spiral excavation was created, the 3-dimensional curve was made visually recognizable, and thereby mistakes in operation were effectively prevented.

(2) Adoption of Rear Body Oscillation Type Joining Device (Pin Joining)
Rear bodies are coupled by pin joining and the excavation is proceeded by shaking the whole right-hand machine in this project (Figure 9). Owing to this, the directions of the rear body and of the tunnel curve are aligned. Consequently, the outbreak could be decreased and the influence to the neighboring ground. Moreover, damage to the segment caused by rub in the tail part was prevented by suppressing deviated pressure of the jack thrust and by securing tail clearance. Additionally, spiral excavation with warping effect on the whole equipment including the front and the rear body was enabled by coupling the rear body with pin joining. Therefore, it was enabled to obtain large spiral force with small ground reaction force.

However, damage to the joint caused by the difference between the movement of right and left machine was concerned with because the bodies were coupled with pins. Hence various types of measuring instruments were installed to measure the behavior during the construction work. This has enabled the machine operation according to the behavior of the joints and led to the prevention of troubles such as damage on the coupling parts in the spiral section.

(3) Adoption of a Shield Jack Oscillating Device (Spiral Jack)
The shield jack (spiral jack) which has the mechanism to eccentricate the shield jack by 2 degrees to the circumferential direction was adopted (Figure 10). Owing to this, the direction in which the shield jack extends and the shape of the spiral curve are aligned and consequently load is not applied to the shield jack and repositioning of the jack is unnecessary. Additionally, if the
jack nearly goes out of the spiral orbit, load is applied to the shield jack and a force to return the shield machine to the spiral curve is generated.

![Figure 10: The Spiral Jack](image)

(4) Suppression of Ground Deformation with Overbreak Filler
During the spiral excavation, the amount of over-excavation becomes about 350 mm. In order to mitigate its influence to the river structure, it was planned to maintain the natural ground by filling the overbreak section with plastic clay gel material, which has been proved in numerous sharp curved line construction works (Figure 11). Additionally, according to the previous analysis, displacement magnitude of the neighboring structures was confirmed within tolerance, owing to this measure.

![Figure 11: The overbreak filler (plastic clay gel material)](image)

(5) Securing Ground Reaction Force Using Mini Packers and Visualization of Excavation Progress
The mini packers (Segment Back Surface Filling Method) were used to promote early adhesion between the natural ground and segment, and to transmit the propulsion reaction force to the natural ground (Figure 12). Additionally, mini packers were also deployed between the tunnels, in order to keep the gap between the two tunnels extremely close to each other (with the gap of 90 mm) constant. In curves and spirals, copy cutter for shield machines are used to cut out the orbit of the shield machine to maintain the shape of the curve. The set value and measured value
of the copy cutter cutting situation during the excavation was visualized in this construction. Owing to this excavation situation visualization system, it was confirmed that necessary outbreak was being secured on real time, and whether the curve shape was maintained as planned.

![Mini packer (Limited injection bag)](image)

Figure 12: Illustration of mini packer use

6. CONCLUSION

By taking the above measures, the world’s first construction work, which was executed by rotating the spiral segment of about 137.4 meter by 90 degrees, was completed within the management value of curve shape in the end of the last September. The construction was executed without any influence to the neighboring ground. Currently they are excavating in tandem toward the arrival shaft. And by taking various other measures as well as the ones described above, sure and secure execution of the spiral excavation was realized. We are going to compare various planned and actual values to evaluate the validity of the management value, relation between the management value and various excavation data, and the excavation management method, and report the result. We hope that the investigation will provide useful information for planning similar construction works.

7. ACKNOWLEDGEMENT

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8. REFERENCES