Tunnelling and Ground Conditions, Abdel Salam (ed.) © *1994 Balkema, Rotterdam, ISBN 90 5410 363 9*

Development of vertical-horizontal shield machine

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ABSTRACT

A vertical-horizontal shield machine has been developed to carry out efficient excavation of shaft and adit tunnels deeper underground.

The vertical-horizontal shield machine consists of a main shield for vertical excavation with a rotatable sphere incorporated in sub-shield for horizontal excavation. After vertical excavation, the sphere rotates 90° to start the sub-shield. This newly developed machine is capable of excavating shafts and adits continuously using only a single machine.

This report describes the vertical-horizontal shield machine, an implementation example of the right-angled rotating shield machine, the first sphere shield machine, and the vertical- horizontal shield machine planned to be the second machine.

1. INTRODUCTION

City underground space is being effectively used to accommodate a large number of city facilities such as power and communication tunnels, gas lines, waterworks and sewage pipes, subways, etc. As the underground space at the shallow and medium-shallow levels becomes more limited, newly planned facilities must be located deeper underground.

Construction work deeper underground involves several problems that cannot be solved by conventional technology because of the high pressure of underground water. The problems of shield excavation construction methods for a 50 m deep tunnel can probably be solved using conventional technology. However, several technical problems remain concerning the shield excavation shaft.

In the case of the pneumatic caisson construction method, although unmanned operation has largely increased due to improvement in remote control technology, there is work that still must be done by man power in a compressed air environment, so that a working depth of 50 m is the limit set by the Labor Sanitation Law. Depending on the geological features, an additional precautions to prevent air leakage are needed even at shallow levels. Furthermore, since excavated sediment is discharged using buckets, excavation efficiency deteriorates as the depth increases, thus lengthening the construction period.

When carrying out shaft excavation using the cast-in-situ diaphragm wall method, a wall length of nearly 100 m is generally needed for floor construction of 50 m because of the deep impermeable ground. This increases both construction period and cost. Furthermore, there are always problems of boiling and heaving, requiring additional precautions to prevent them.

Whichever method is adopted, it is necessary to improve the foundation and cut the diaphragm for protection at the time of advancement. So, the greater the depth at which the work is performed, the more dangerous it becomes. Under such circumstances, the development of advanced shield technology for safe, quick and secure operation is required.

The "Vertical-Horizontal Shield Machine" described here is a machine that excavates the shaft before performing continuous excavation of the adits, and has been developed with the purpose of rationalizing shield excavation shaft construction at greater underground depths.

This report describes the vertical-horizontal shield machine, the implementation example of the right-angled rotating shield machine, the first sphere shield machine, and the vertical- horizontal shield machine planned to be the second machine.

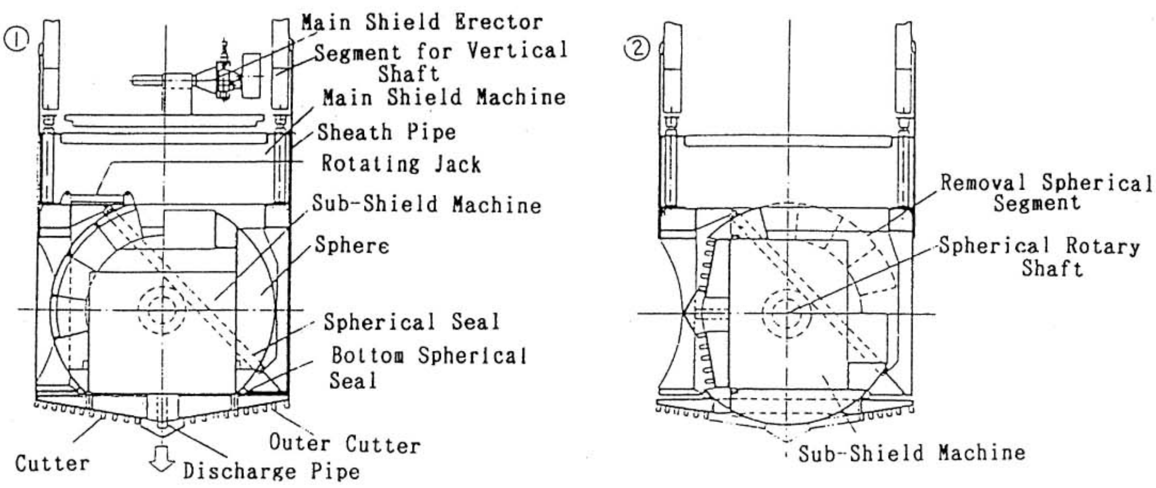

Figure 1. Outline drawing of vertical-horizontal continuous shield machine

2. VERTICAL-HORIZONTAL SHIELD MACHINE

2.1 Basic structure

As shown in Fig. 1, the vertical-horizontal shield machine consists of a main shield for vertical excavation with an incorporated sphere that houses a sub-shield for horizontal excavation.

When the main shield reaches the specified depth, the sphere is rotated 90° to start the sub-shield for horizontal excavation. During vertical excavation or at the time of sphere rotation, stopped water inside the machine is held by a seal.

The slurry shield system is used for the main shield, and the reverse circulation drill method, with an excellent record in large aperture shaft construction, is used for vertical excavation. Excavated sediment is collected at the center of the cutter before being discharged by the pump. Furthermore, the cutter and the cutter driving device used in the main shield are designed to be used jointly for the sub-shield.

The main shield consists of a sphere with the built-in sub-shield, a vertical shield frame to house the sphere, sheath pipes to protect the frame, and an outer cutter for vertical excavation as shown in Fig. 2.

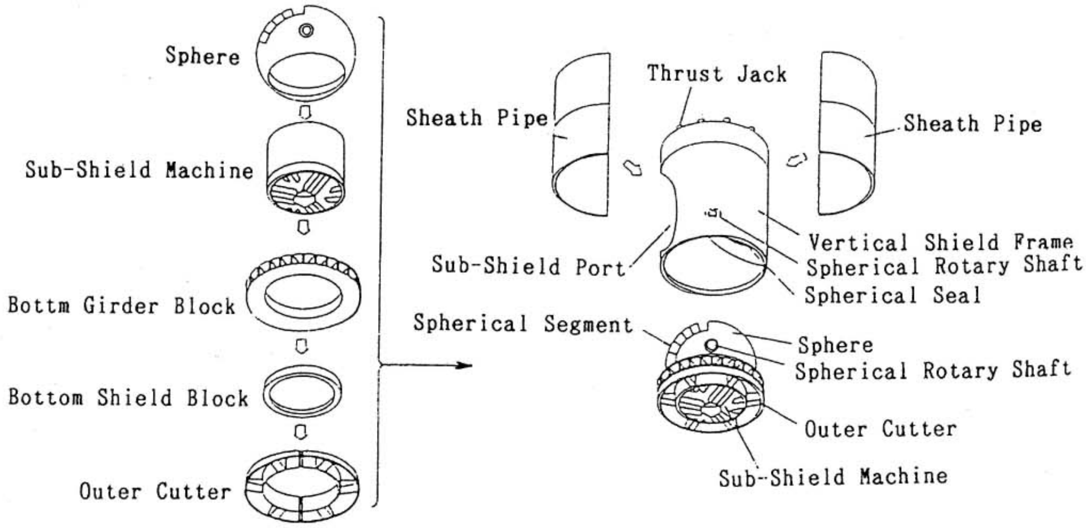

Figure 2. Structural exploded view of main shield machine

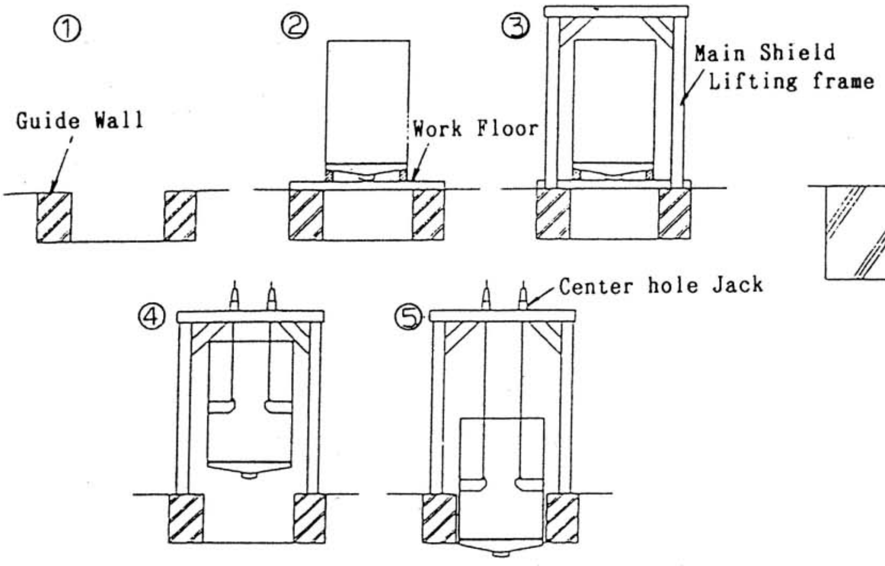

Figure 3. Excavation procedure of main shield machine

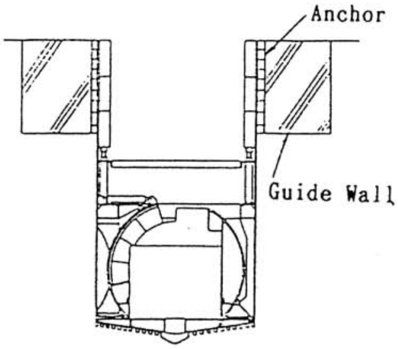

Figure 4. Shaft excavation condition

2.2 Excavation procedures

Vertical-horizontal shield excavation procedures are described below.

(1) Install the main shield lifting frame on the ground as shown in Fig. 3 and assemble with the main shield at the inverted position. At the time of initial excavation, suspend the shield machine with the main shield lifting frame and let the shield machine lower under its own weight while preventing rolling and pitching of the machine by jack operation.

(2) As shown in Fig. 4, after the tail of the main shield passes through the guide wall, start excavation using the thrust jack while applying inverse force to the segment in the same manner as for an ordinary shield machine, when the buoyancy overcomes the weight of the shield machine. To make use of the weight of the main shield lifting frame as the inverse force, keep the segment and the main shield lifting frame firmly tied with an anchor, etc.

(3) Once the main shield reaches the adit crown position, fix the sheath pipe to the segment, lower the main shield with the thrust jack, and expose the cutting part of the vertical shield frame as the opening for the sub-shield.

(4) Upon completion of vertical excavation, pull out the connecting pin that connects the outer cutter to the cutter head of the sub-shield using the hydraulic jack to remove the outer cutter from the sub-shield machine. Leave the outer cutter, which is no longer needed, at the bottom of the vertical shaft, use the thrust jack of the sub-shield to slide the entire sub-shield upward before storing it into the sphere rotating locus.

(5) Turn the sphere 90° with the rotating jack so that the cutter head comes from the downward position to the horizontal position. Then successively remove the no longer needed sphere segments by regaining the rotating jack.

(6) After the sphere is rotated, press the thrust jack of the sub-shield against the steel wall for inverse force inside the sphere to push down the sub-shield from the sphere, and then weld the tail plate, mount the erector, etc., to complete the sub-shield. Install the temporarily assembled steel segment inside the sub-shield, and use it as the inverse force to start the sub-shield.

2.3 Shield method features

(1) The size of the shaft method used with this method makes it possible to reduce the thickness of the lining by using the segment in the shaft, with the outer diameter being reduced 50-70% as compared to conventional

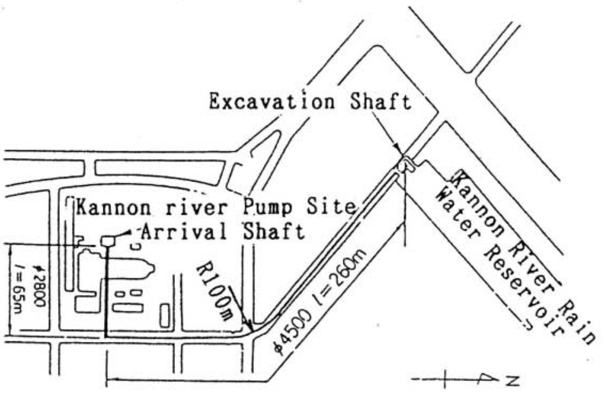

Figure 5. Excavation route of right angled rotating shield machine

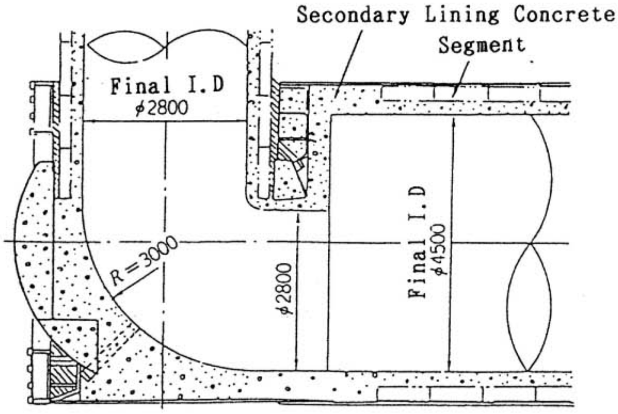

Figure 6. Final tunnel shape of right angled rotating shield machine

methods. The reduction in shaft size is more economical not only because it leads to the reduction of land cost but also because it reduces the quantity of dug up soil.

(2) The construction of the shaft by the shield method shortens the construction period by 50% as compared with conventional methods, reducing field expenses and alleviating public inconvenience, such as road blockage, etc.

(3) The construction cost includes the fixed cost of the shield machine and variable costs depending on the depth of the shaft. The shaft excavation cost using this method is more economical as the depth increases, with the depth of 30-40 m being the diverging point.

(4) Because there are no dangerous jobs such as cutting the diaphragm at the time of start, etc., higher reliability can be obtained for work .at greater depths. Higher water pressure can be appropriately dealt with by using the mechanical seal. Furthermore, there is no need to worry about workers health and air leakage due to atmospheric pressure as in the case of the pneumatic caisson construction method.

3. IMPLEMENTATION EXAMPLE OF RIGHT-ANGLED ROTATING SHIELD MACHINE

3.1 Construction work

The right-angled rotating shield machine has basically the same structure as the vertical-horizontal shield machine. However, instead of excavating a shaft, it excavates a tunnel at a right angle from the original tunnel and parallel to the surface.

One example of a tunnel made by the right-angled rotating shield machine is the conveyance ditch in Kawasaki City, connecting the Kannongawa rain water reservoir and the pump site, which also works as a rain water retaining pipe. The outline of the construction work is shown below.

Finished tunnel inner diameter x total length

* Main shield: ø4500 mm x 260 m
* Sub-shield: ø2800 mm x 65 m

Soil characteristics: Silt (N value: 2 - 4)
Soil depth: 11.5 m (average)
The right-angled rotating shield machine was used for the following reasons.

(1) Low construction cost

(2) Shortest route and shortest construction period

(3) No need of work on the road

The excavation route is shown in Fig. 5. Because of the foundation pile driven in the site where the tunnel bends vertically, it was difficult to penetrate the sharp curve. Furthermore, because the site was the entrance of a factory and the pipes buried under the ground had to be shifted, it was impossible to make the rotating shaft from the ground.

Note: The tunnel diameter of the right-angled rotating shield machine is reduced from the main

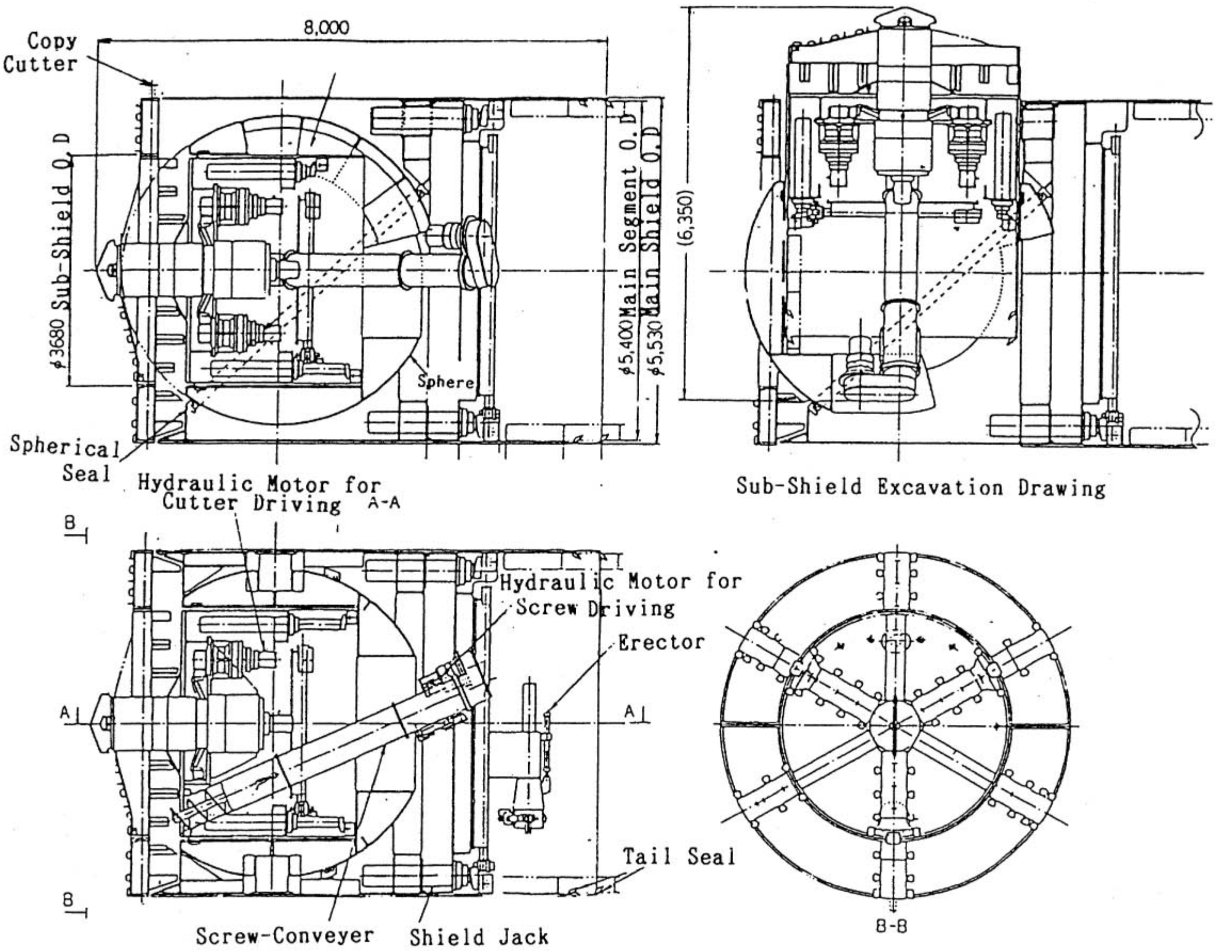

Figure 7. Overall assembly drawing of right angled rotating shield machine

shield to the sub-shield, but since this is a storage pipe, there are no functional problems. The final shape is shown in Fig. 6.

3.2 Structural features

As shown in Fig. 7, the outer diameters of the right-angled rotating shield machine are main shield: ⌀5530 mm, sub-shield: ⌀3680 mm. The right-angled rotating shield machine has basically the same structure as the vertical-horizontal shield machine, but the mud-pressure type machine is used because of the adit excavation carried out using the main shield, considering soil condition, installment space for slurry treatment plant, etc. Hence, the sub-shield is mounted with the screw conveyor to be used also as the muck discharging device of the main shield.

Moreover, the cutter driving device is also used for the sub-shield and main shield as in the case of the vertical-horizontal shield machine. However, since the torque of the mounted cutter should enable excavation with the main shield, the cutter must have a higher excavation capacity than a vertical-horizontal shield machine with the same diameter.

Therefore, the sub-shield cutter torque mounted may be excessively large device for the sub-shield for adit excavation, but the torque may prove insufficient for the main shield excavation capacity. In this construction work, however, the soil was soft and there was no need to mount the excessively high torque for the main shield, so that appropriate measures could be taken. So, compared with the vertical-horizontal shield machine, the right-angled rotating shield machine has a narrower selection range in terms of cutter torque, such as the outer diameter ratio between the main shield and sub-shield, the excavated soil characteristics, type of shield machine, etc.

Fig. 5 shows a curve of R 100 m in the

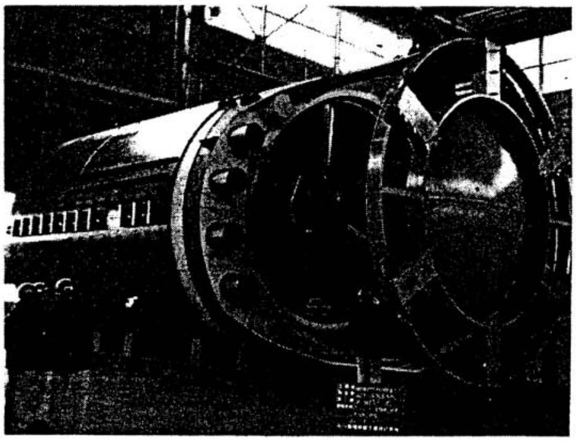

Figure 8. Photo of completed right angled rotating shield machine

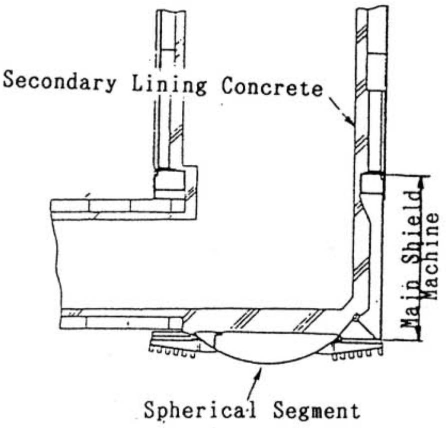

Figure 9. Final shaft shape of vertical-horizontal continuous shield

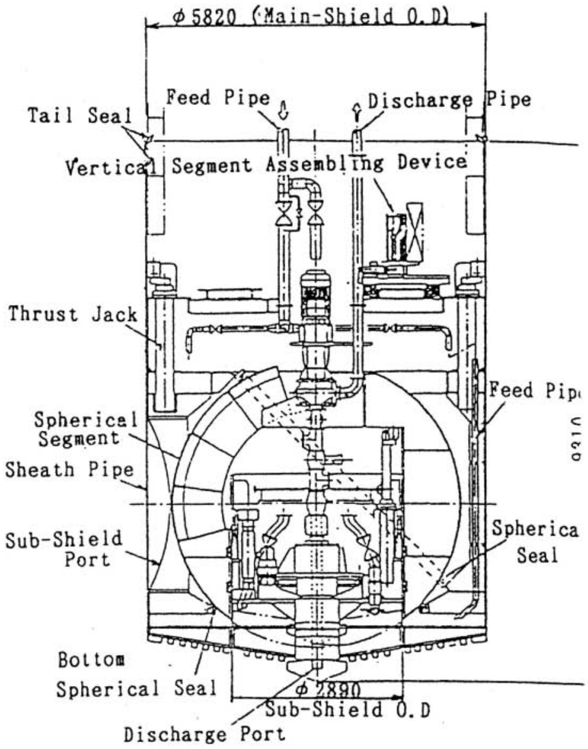

Figure 10. Overall assembly drawing of vertical-horizontal shield machine

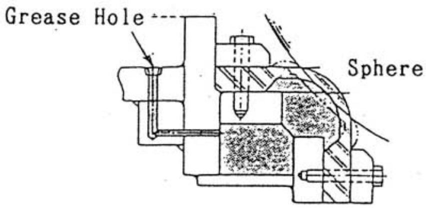

Figure 11. Bottom rotary seal

excavation route, requiring measures for curve excavation using the main shield, which is quite unlike the vertical-horizontal shield machine.

The over cut device is designed to have the slide rod, located in the outer cutter, connected to the copy cutter jack installed on the sub-shield cutter, lowing the bit to go in and out at the end of the slide rod to reach the outside of the outer cutter.

Furthermore, since the sphere is installed inside the shield, the machine length becomes longer than the normal shield, calling for measures to keep the machine length short. The shield jack of the main shield machine is located here at the front most position. However, placed at this position, the jack interferes during sub-shield start. The jack is, therefore, stored in the outer drum, and is designed to slide backward together with the outer drum by securing the air seal of the machine after the completion of main shield excavation. The structure is shown by the four cylindrical bodies in Fig. Fig. 8

4. INPLEMENTATION EXAMPLE OF VERTICAL-HORIZONTAL SHIELD MACHINE

4.1 Construction work

The first vertical-horizontal shield machine planned to be adopted in the sewage construction work in Tokyo is described here. The outline of the construction work is shown below.
shaft inner diameter x shaft depth (Main shield excavation): ⌀5000 mm x 39 m

Finished tunnel inner diameter x Total length (Sub-shield excavation): ⌀2450 mm x 433 m
Soil characteristics: Silt, sand layer, gravel layer
Tunnel minimum curve: R 10 m

Furthermore, the final structure of the vertical shaft is designed to have a steel structure by combining the main shield frame with the sphere bottom as shown in Fig. 9, while dismantling the internal structural materials of the sphere, etc. inside the machine but partially leaving the sphere at the bottom of the vertical shaft, in order to withstand the rising pressure of the underground water. This allows, unlike the final shape of the right-angled rotating shield machine, an effective passage space to the adit from the shaft.

4.2 Structural features

As shown in Fig. 10, the outer diameters of the vertical-horizontal shield machine are main shield: ;820 mm, sub-shield: ⌀2890 mm.

The slurry shield machine is also used for the sub-shield so that a muck discharging system can be used with fluid transportation during main shield shaft excavation, the same as in the reverse circulation drilling method.

As for the seals of the sphere rotating section, the bottom sphere seal is installed to dismantle the internal structural materials such as the sphere, etc., in the machine after the start of the sub-shield. Also, a sphere seal is installed diagonally at the upper part to stop water during main shield vertical excavation and sphere rotation.

The inflating-type rubber seal, shown in Fig. 11, is adopted as the bottom sphere seal and is designed to stop water by operating the internal pressure of the seal, into which grease is injected. The reason why the seal has this shape is because it is necessary to prevent the cutting part of the phere of the cutter from damaging the seal when passing through the seal. The durability and water stopping performance have been fully confirmed through an element performance confirmation test, with the water stopping performance of the cutting part of the sphere found to be 0.98 MPa.

Furthermore, it is necessary to stop water at the opening for the sub-shield starting port during dismantling inside the machine. Water is stopped by the entrance segment. The entrance segment, as shown in Fig. 12 and Fig. 13, is a special segment installed with the partition plate required for injecting back-filling material to stop the water at the tail clearance between the adit segment and the main shield shaft opening after the sub-shield passes out of the main shield.

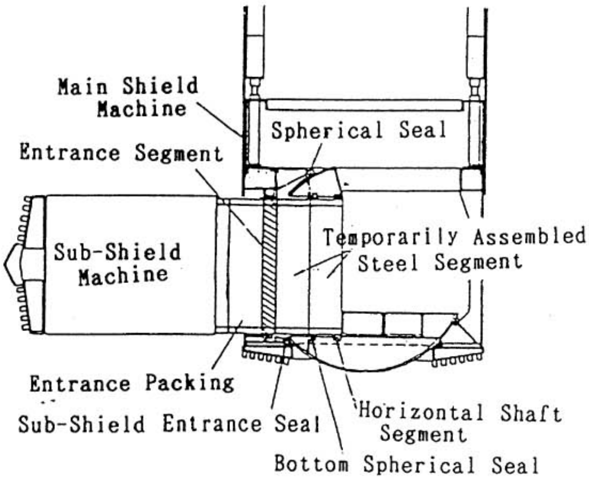

Figure 12. Installation drawing of entrance segment

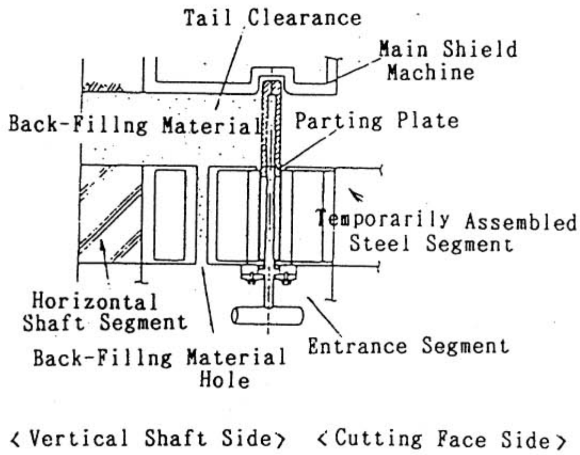

Figure 13. Detailed drawing of entrance segment water sealing section

Before excavation, the temporarily assembled steel segment is fully assembled from inside the shaft, and the entrance segment is erected before the sub-shield passes through the main shield, while the partition plate is pushed down immediately after the passage of the sub-shield to inject into the tail clearance the back-filling material, which is then solidified to stop the water.

The cutter driving device for the sub-shield is also used for the main shield, but the torque of the cutter has a smaller excavation capacity than that of the right-angled rotating shield machine used for adit excavation. It has been confirmed through the vertical shaft excavation experiment that the cutter torque needed for shaft excavation is approximately one-tenth of the cutter torque needed for adit excavation.

The sub-shield is designed as an articulate type capable of 9° articulation in order to carry out sharp curve excavation at 4 places with a minimum curve of R 10 m using the sub-shield. The installation of an articulate-type sphere shield in the sub-shield machine has widened the application range of construction conditions.

5. CONCLUSION

In addition to the vertical-horizontal shield machine and right-angled rotating shield machine introduced in this paper, there are several other variations of the sphere shield under development, such as a long-distance excavation shield machine whose cutter bit can be replaced several times in the tunnel by using the sphere. Various other ideas concerning construction methods with a sphere shield have also been thought up, so that the sphere shield construction method is now highly expected to play a significant role in the building of underground structures deeper underground.

However, development of the sphere shield construction methods, such as the vertical-horizontal shield machine, has just started with only a few implementation examples. The method can thus be considered as under development. We are determined to continue our research and development to apply this method to construction work deep underground and to solve various other problems such as machine safety, effective workability, etc., in order to contribute to wider application of this method.

Finally, we would like to express our sincere thanks to all concerned people for their cooperation throughout the process of this development.