

Development of Rectangular Shield

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Various shield tunneling methods have been introduced and applied practically in recent years for reduction of cost and rationalization. The rectangular shield is one of the machines for those methods. Since a rectangular-section tunnel needs less boring area and the space in it can be utilized more compared to a circular-section tunnel, various mechanisms of the rectangular shield have been developed and applied to practical works. Komatsu has also manufactured three rectangular shields. The shield No. 3 is the largest rectangular shield in Japan. In this paper, the rectangular tunneling mechanism and segment erector which we have newly developed are mainly introduced.

Key Words: Rectangular Section, Rectangular Shield, Wagging Cutting, Overcutter, Erector, Position Control

1. Introduction

Various boring mechanisms of the rectangular shield such as the multi-circle type, eccentric multi-shaft type, eccentric double-shaft type, cylinder type, etc. have been developed and applied to practical work. Komatsu have also developed the rectangular boring mechanism consisting of the “wagging cutter head” and “overcutter” and the multi-operation segment erector for rectangular segments. **Table 1** shows the rectangular shields which Komatsu manufactured. They are developed steadily by solving the problems found during the actual operation and installing new mechanisms. The features of the rectangular shield are explained below, by using shield No. 3 as a main example.

2. Rectangular shield

The rectangular shield was developed to meet the following needs for cost reduction.

- ① Execution of work under restriction (Occupied width, covering with soil, etc.)
- ② Reduction of dirt and sand to be moved
- ③ Rationalization of use of section of tunnel (See **Fig. 1**)

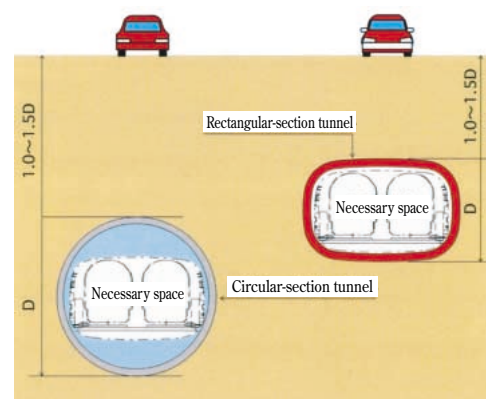
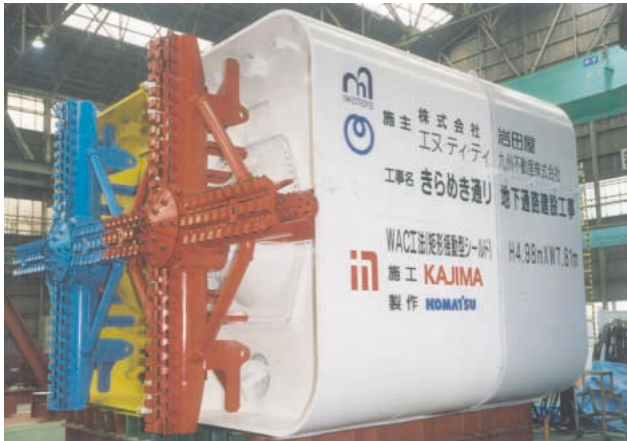


Fig. 1 Comparison of rectangular and circular sections

Table 1 Rectangular shields manufactured by Komatsu



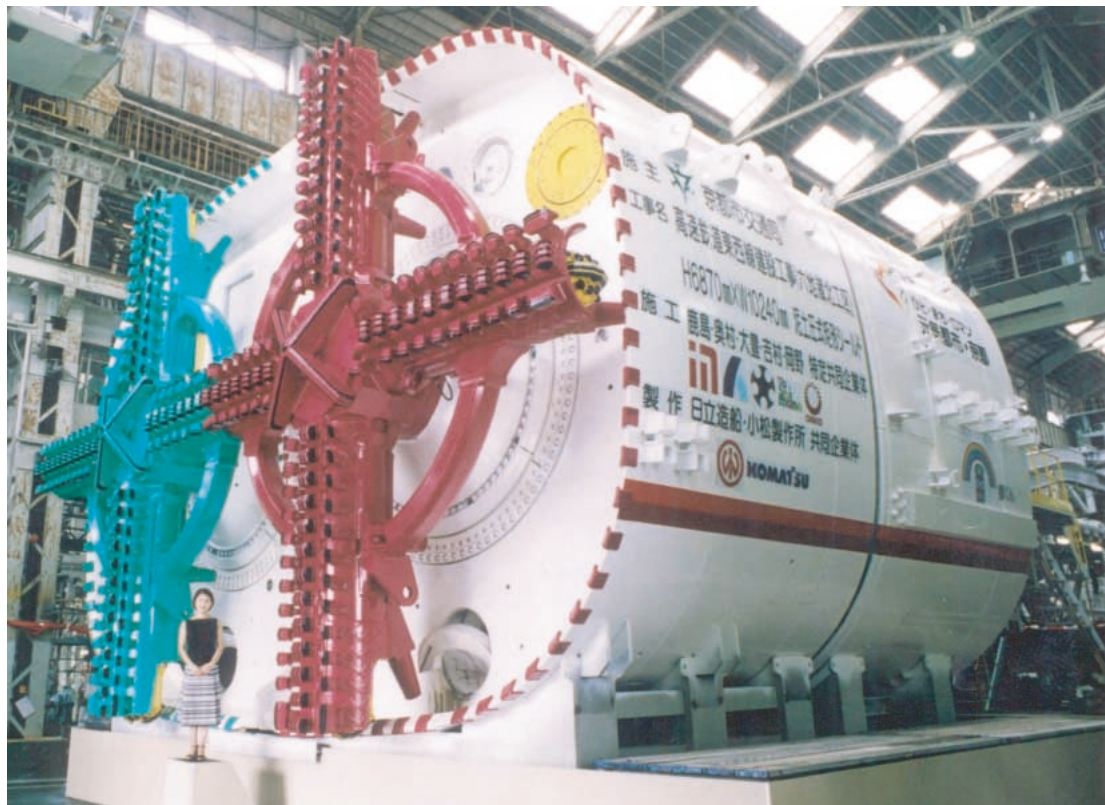
Rectangular shield No. 1 (TK781PMX-1)

| | |
|------------------------------|---|
| Outside dimensions of shield | 7810 mm wide x 4980 mm high |
| Jobsite/Use | Fukuoka City/Undercarriage passage |
| Boring distance/Type of soil | 117 m/Sandy soil |
| Capacity | Total thrust: 41160 kN, Torque: 2813 kN-m |
| Operation period | 1998/05 – 1998/08 |



Rectangular shield No. 2 (TK490PMX-1)

| | |
|------------------------------|---|
| Outside dimensions of shield | 4900 mm wide x 4300 mm high |
| Jobsite/Use | Kyoto City/Underground river |
| Boring distance/Type of soil | 90.7 m/Gravelly soil |
| Capacity | Total thrust: 26460 kN, Torque: 4944 kN-m |
| Operation period | 2000/10 – 2001/01 |



Rectangular shield No. 3 (TK1024PMX-1)

| | | | |
|------------------------------|-------------------------------|------------------|--|
| Outside dimensions of shield | 10240 mm wide x 6870 mm high | Capacity | Total thrust: 77450 kN, Torque: 10025 kN-m |
| Jobsite/Use | Uji City to Kyoto City/Subway | Operation period | 2002/03 – 2003/03 (Plan) |
| Boring distance/Type of soil | 759.6 m/Gravelly soil | | |

Since the shield bores a tunnel by the following main processes, it has the functions (devices) for those processes (See Fig. 2).

- ① Excavating: Process of cutting ground — (Cutter head)
- ② Thrusting: Process of controlling position of shield and thrust it under ground — (Shield jack, articulated jack)
- ③ Discharge of soil: Process of collecting cut dirt and sand and sending them to above ground — (Screw conveyor)
- ④ Lining: Process of assembling segments to support ground and receive reaction force of thrust — (Erector)

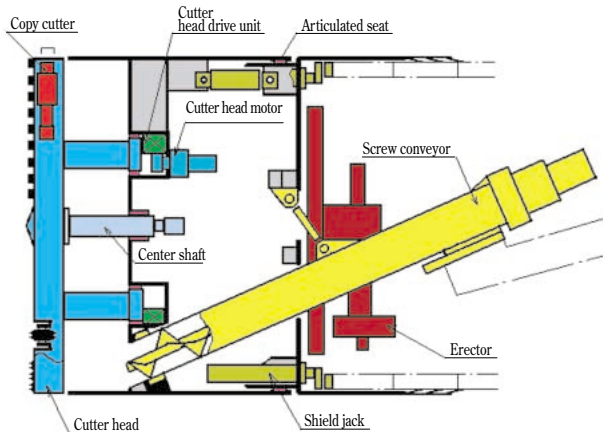


Fig. 2 Configuration of shield

Usually, processes ① – ③ are executed simultaneously, then process ④ is executed, and this cycle is repeated.

Since ① the excavating and ④ the lining processes for the conventional circular shield must be changed for the rectangular shield, we selected them as the points of development of the rectangular shield.

3. Development of rectangular shield

3.1 Rectangular-section boring

1) Wagging cutter head

<Background of development>

Dirt and sand can be cut most efficiently with a rotational motion. If a rotary cutter head shown in Fig. 3 – (a) (a cutter head which rotates continuously) is used to bore a rectangular-section tunnel, large parts (hatched parts) are left uncut, since the spoke length of the rotary cutter is fixed.

On the other hand, if a wagging cutter head (a cutter head which wags by a certain angle) is applied, the length of each spoke can be set for its wagging range. Accordingly, the uncut parts are reduced to a degree that they are not problems practically, compared to the parts left uncut by the circular cutter head (See Fig. 3 – (b)). The parts which are not cut with the rectangular shield are cut with the overcutter shown in Fig. 4.

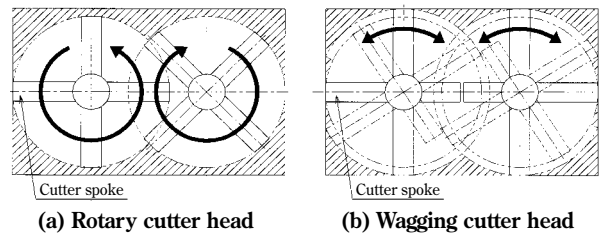


Fig. 3 Comparison of cutting sections

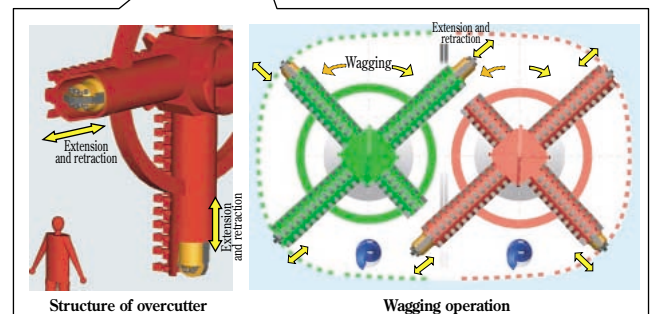
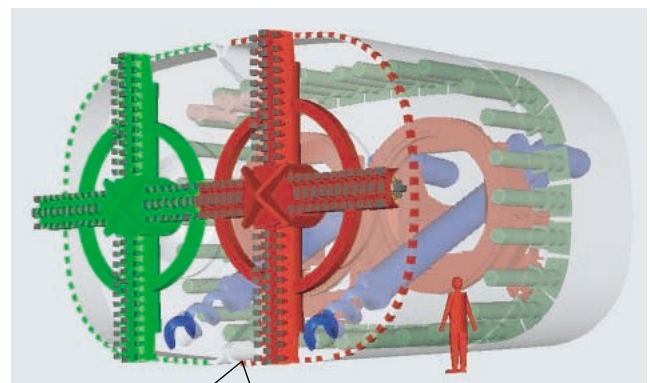


Fig. 4 Wagging cutting operation of rectangular shield No. 3

<Driving cutter head with jack>

The wagging cutter head does not need to be rotated and can be driven with jacks through torque arms. Accordingly, the structure of the wagging cutter head consisting of the jacks and pins is simpler than the precise structure of the conventional rotary cutter head consisting of a motor and gears (See Fig. 5).

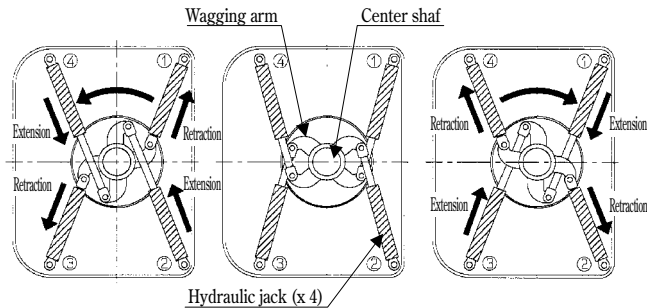


Fig. 5 Wagging drive

<Consideration of necessary torque>

While the output torque of the rotary cutter head is constant, that of the wagging cutter head changes with the wagging angle as shown in formula 1.

$$T = R \times F \cos\theta \dots (\text{Formula 1})$$

$$(\theta = 90^\circ + (\beta - \alpha))$$

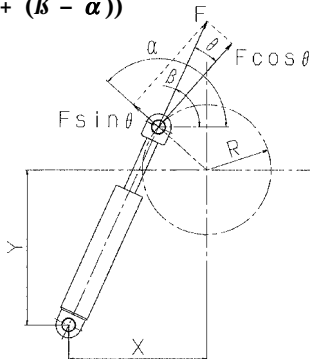


Fig. 6 Basic drawing for calculation of wagging jack torque

Accordingly, when the jacks are arranged as shown in Fig. 5, the generated torque is reduced as the wagging angle increases as shown in Fig. 11. On the other hand, the stroke of the overcutter to cut the uncut parts increases as the wagging angle increases and the necessary torque becomes maximum when the cutter returns. As a result, if the jacks are arranged in this way, the torque tends to be insufficient when the moving direction of the cutter is changed. This matter must be considered when high torque is required.

<Background of development of assist type>

To solve the above problem, we employed the wagging system of assist type for rectangular shield No. 2 and after. The arrangement of the jacks of rectangular shield No. 3 is shown in Fig. 7.

In this type, two wagging jacks are used and two assist jacks are so added that their center line will be at the rotation center of the cutter head when the wagging angle is zero

degree. The torque generated by the assist jacks becomes zero when the wagging angle is zero degree and becomes maximum when the cutter changes its moving direction.

The method of controlling the jacks is explained below (See Fig. 7).

- ① Within a certain wagging angle from the neutral position (e.g. ± 15 degrees), the cutter head is wagged with only the wagging jacks (The assist jacks are in neutral hydraulically).
- ② Out of the above wagging angle, the assist jacks are actuated to compensate the wagging jacks for reduction of the torque. In rectangular shield No. 3, the two assist jacks are actuated in two steps so that the torque will increase as the wagging angle increases.

An interlock is installed to stop the operation and prevent both cutter heads from interfering with each other when their wagging angles differ more than five degrees.

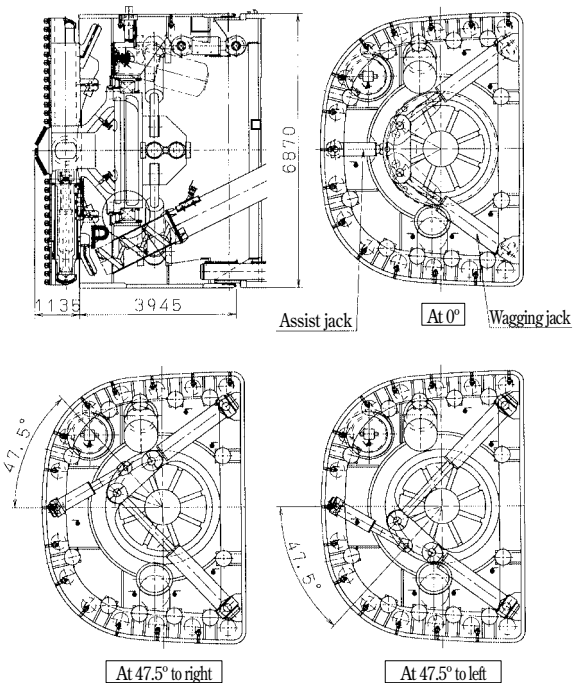


Fig. 7 Drive unit of rectangular shield No. 3

<Calculation of usable torque>

The torque characteristics of rectangular shield No. 3 with assist jacks are shown in Fig. 8.

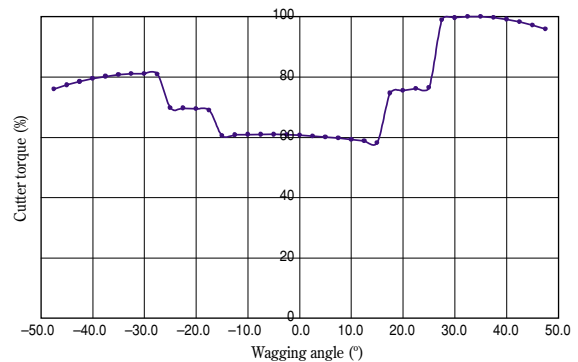


Fig. 8 Torque characteristics (Rectangular shield No. 3)

For reference, the drive units of rectangular shields No. 1 and No. 2 are shown in Fig. 9 and Fig. 10 and their torque characteristics are shown in Fig. 11 and Fig. 12 respectively.

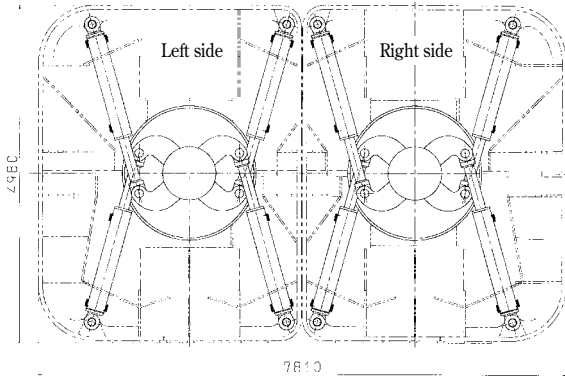


Fig. 9 Drive unit of rectangular shield No. 1

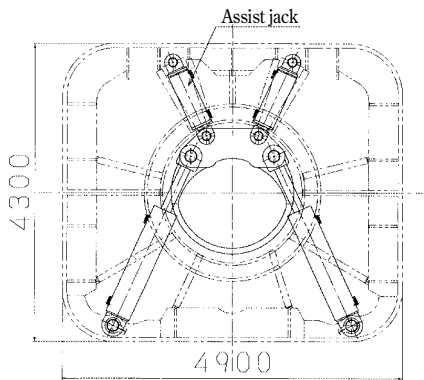


Fig. 10 Drive unit of rectangular shield No. 2

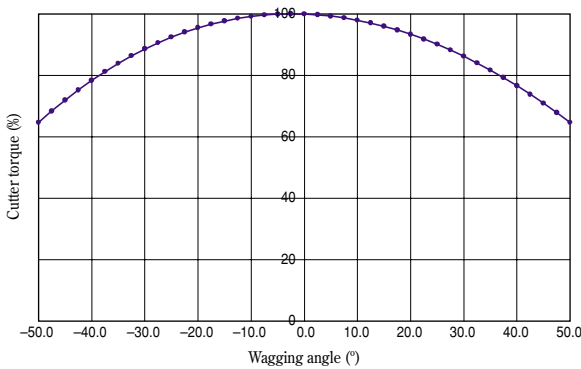


Fig. 11 Torque characteristics (Rectangular shield No. 1)

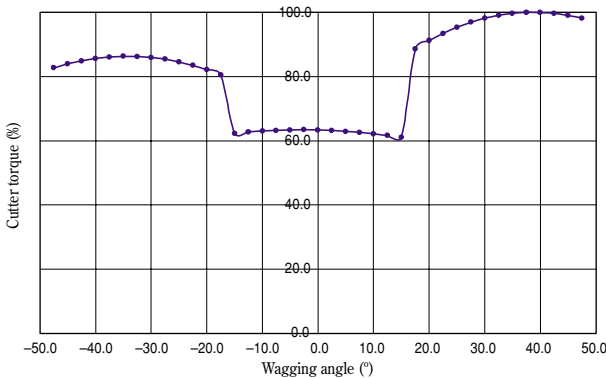


Fig. 12 Torque characteristics (Rectangular shield No. 2)

2) Overcutter

<Mechanism of overcutter>

Although the wagging cutter head leaves less parts uncut than the rotary cutter head, the uncut parts must be cut with auxiliary devices. The cutting mechanism which we recently developed cuts the uncut parts with the overcutters (See Fig. 13). The hydraulic jacks of the overcutters are operated according to the wagging angle of the cutter head to cut along the profile of the rectangular section.

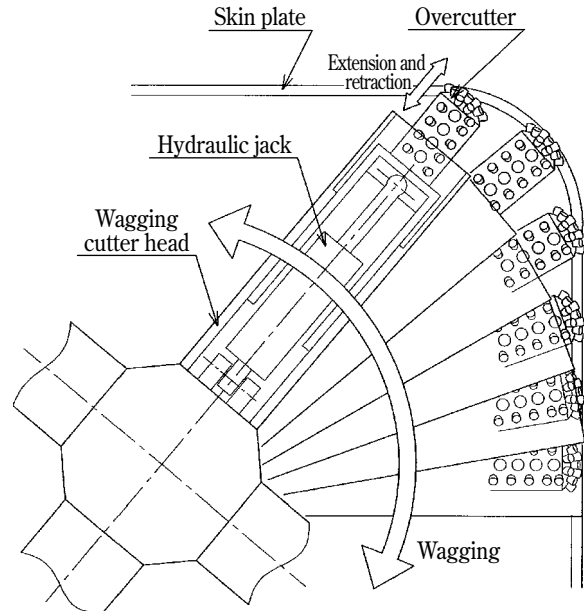


Fig. 13 Operation of overcutter

<Control of overcutter stroke>

The overcutter stroke is controlled automatically by linking extension and retraction of the hydraulic jack with the wagging angle. The configuration of this control unit is shown in Fig. 14.

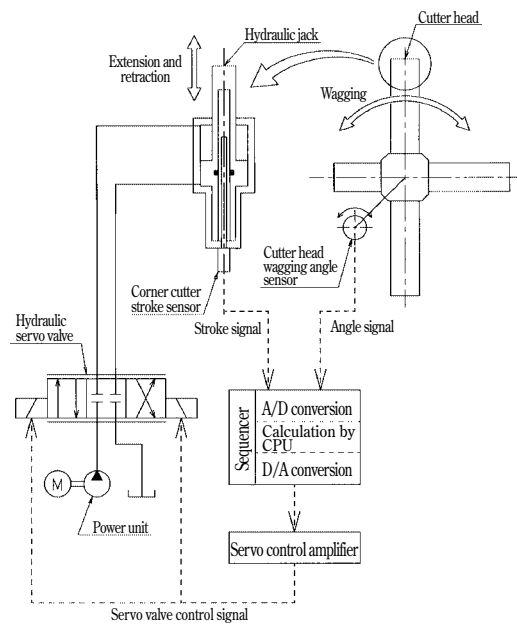


Fig. 14 Configuration of overcutter control unit

The control unit consists of the overcutter stroke sensor, cutter head wagging angle sensor, sequencer, oil pressure servo valve, servo control amplifier, etc.

The overcutter stroke is controlled by the following data and the data fed back from the oil pressure servo valve.

- ① Target stroke in accordance with wagging angle
- ② Measured overcutter stroke.

The target stroke can be set by the following methods.

- ① Successive calculation method (Real-time calculation from wagging angle)
- ② Map method (Reading of value corresponding to wagging angle)

We employ ② Map method for higher response and can reduce the deviation from the target stroke of the overcutter to 20 mm or less.

<Application to long-distance boring>

The boring distance of rectangular shield No. 3 is about seven times as long as that of No. 1 and No. 2 and the total number of operations of the overcutter of No. 3 reaches 80,000.

Considering this matter, we executed a durability test on the full-sized models of the sliding parts of the rods and dirt and sand seals before manufacturing the shield actually. For the test, we applied the expected load to the simulated spoke in a pressure container filled with dirt, sand, and water, then slid the spoke 100,000 times and confirmed that the sliding parts and dirt and sand seals are free from abnormality (See Fig. 15 and Fig. 16).

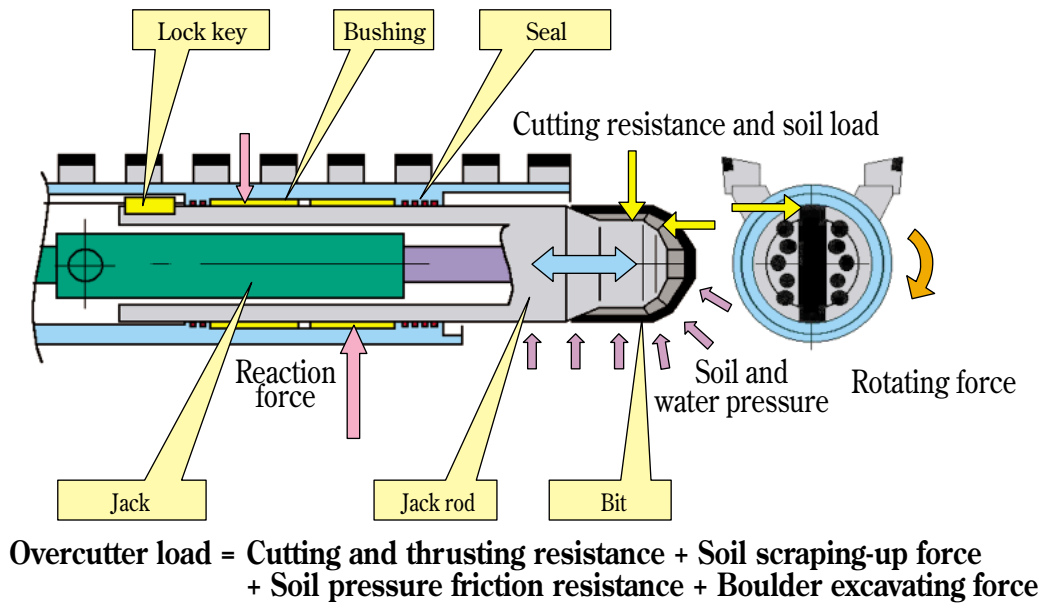


Fig. 15 Expected overcutter load

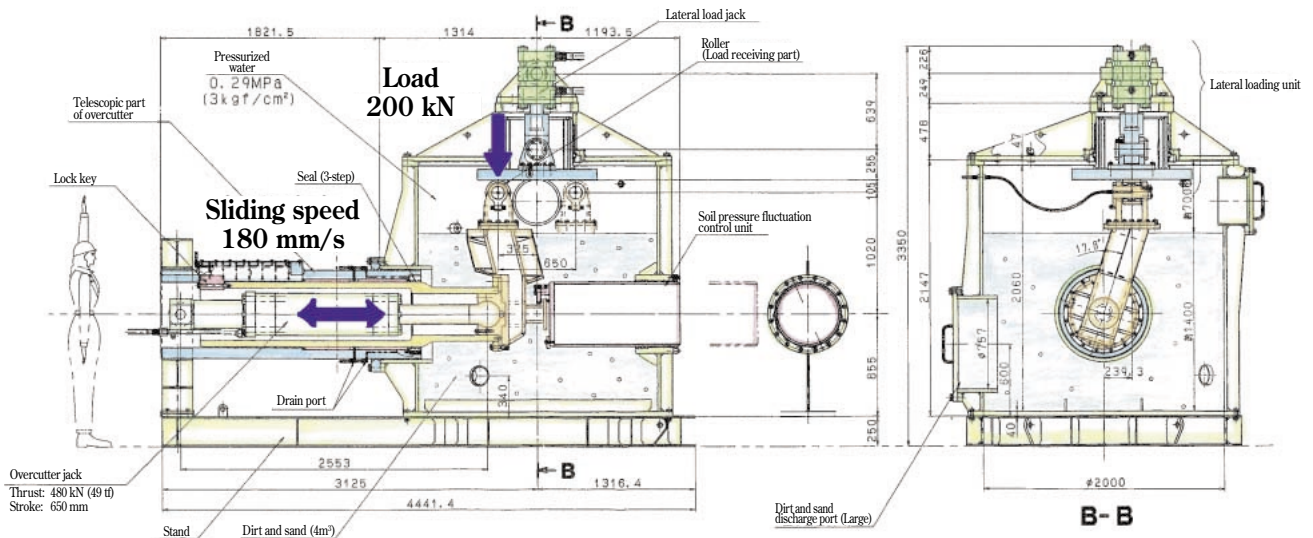


Fig. 16 Overcutter testing device

The test result is shown in **Fig. 17** and **Fig. 18**. These figures show that wear of the bushings and rods and durability of the dirt and sand seals have no problems. **Fig. 19** shows the lubricating oil circulation system of the sliding parts.

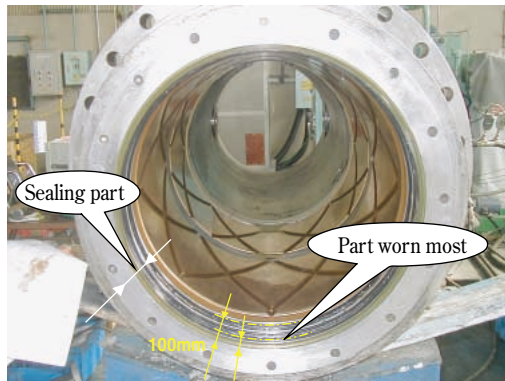


Fig. 17 Bushing slid 100,000 times

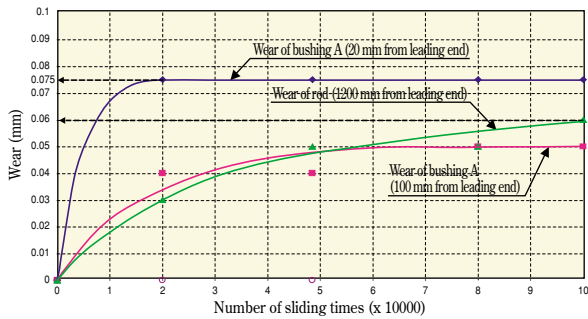


Fig. 18 Graph of wear

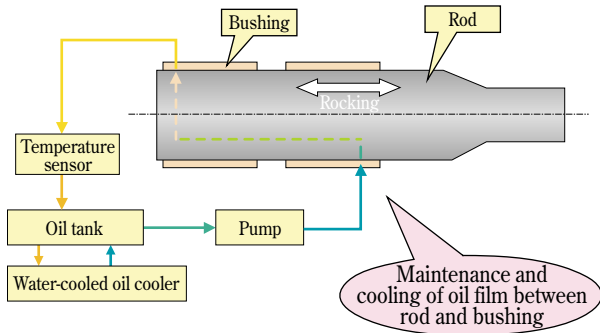


Fig. 19 Circulation of lubricating oil for sliding surfaces

3.2 Lining

<Addition of lateral sliding and bending operations>

When the circular shield is used, the necessary basic operations of the erector are ① swing and ② radial extension and retraction (See **Fig. 20**), since arched segments are used. When the rectangular shield is used, however, the segments cannot be assembled with only the above two operations, since those segments are L-shaped or flat. In addition, since the weight of each segment for rectangular shield No. 3 was the maximum of seven tons, the erector had to have sufficient rigidity and strength.

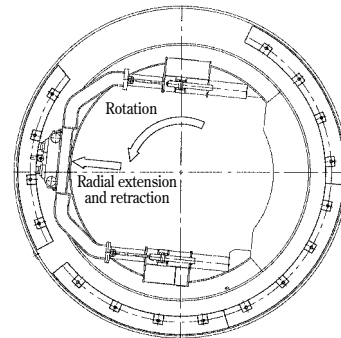


Fig. 20 Assembly of circular segments

Accordingly, we attached the following new features to the erector of rectangular shield No. 3 for 6 operations shown in **Fig. 23** on the next page.

- ① Function of sliding and bending the erector head laterally on a gate frame
- ② Function of finely adjusting the longitudinal and lateral fine slide
- ③ Direct acting bearing to increase rigidity and reduce sliding resistance

<Result of lining test>

After assembling the rectangular shield in the factory, we executed the lining test with the segments for the actual boring work (See **Fig. 21**). It took two hours to assemble one ring. From the result of the examination of the cycle time in advance and improvement of the skill in the field, we believe that the assembly time can be shortened by 30 - 40%, however.



Fig. 21 Assembly test of segment (Equivalent to Step 11 in **Fig. 24**)

<Erectors of rectangular shields No. 1 and No. 2>

Since the segments used for rectangular shields No. 1 and No. 2 were light (about 1/7 of the weight of the segments for rectangular shield No. 3), we employed a cantilever-type erectors which were reducible in size (See Fig. 22). We confirmed that rectangular shield No. 1 was able to assemble one ring in one hour and No. 2 was able to assemble one ring in 40 minutes.

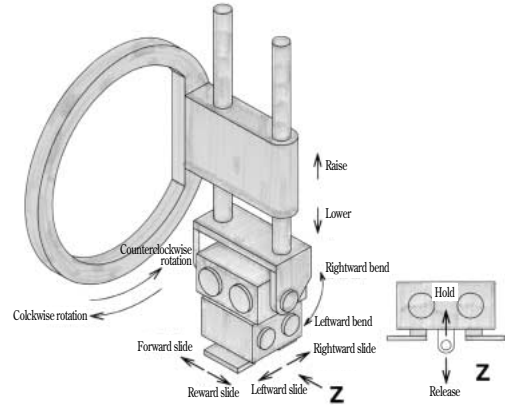


Fig. 22 Erector of rectangular shield No. 1 and 2 (Cantilever type)

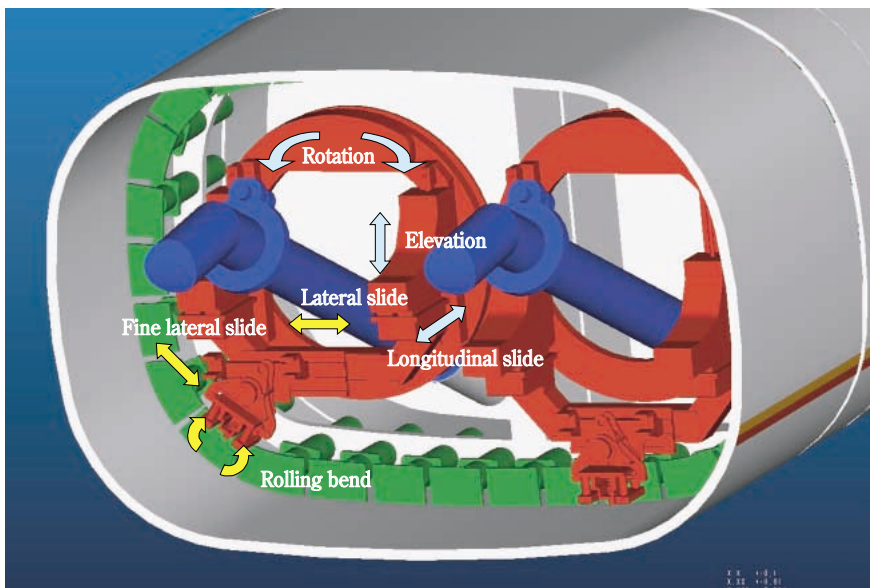


Fig. 23 Erector of rectangular shield No. 3

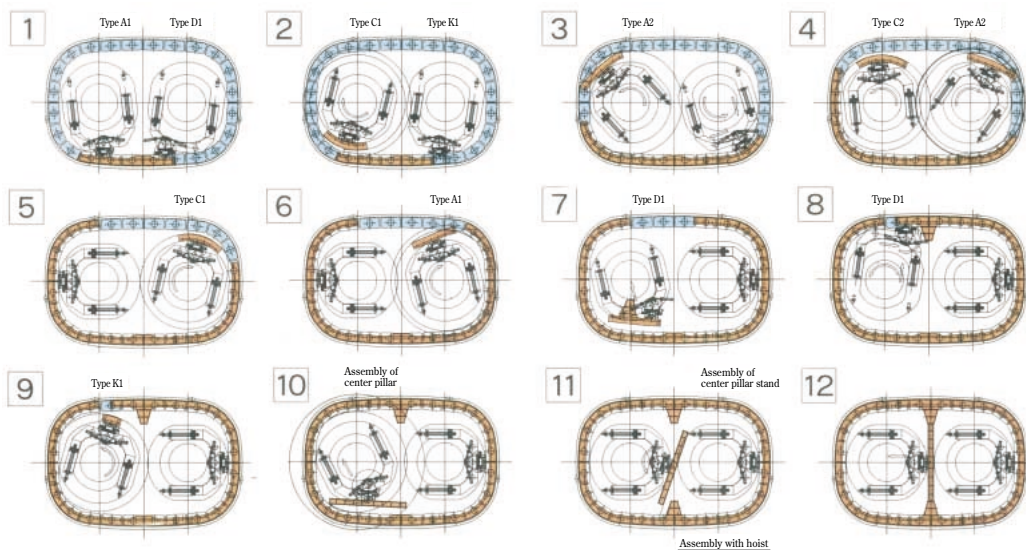


Fig. 24 Example of assembly of reuse criteria segments (15-piece segment for rectangular shield No. 3)

4. Conclusion

Rectangular shields No. 1 and No. 2 introduced in this report have finished their work and are evaluated highly by our customers. Rectangular shield No. 3 is under construction in the field and will start operation next spring. We intend to develop and supply more shields which meet the working conditions and users' requirements, utilizing our experience and technologies.

Introduction of the writers

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[A few words from the writers]

Presentation of technologies to meet users' needs and advance development of the elements to support those technologies are effective tools to receive orders for projects similar to those described above. It is hard, in fact, to develop each machine within the limited period and make a profit on it. We are very glad, however, that we have been working on the machine when it is completed. We will present and develop more technologies, including working methods.