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Construction of extremely close-set tunnels using the muddy soil pressure balanced Rectangular Shield Method

Bau von Tunnels in extremer Englage mit rechteckigem Erddruckschild

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ABSTRACT: This paper describes the principle and features of the DPLEX shield method. An improved version of the EPB shield method, the new method can be used to build tunnels of virtually any cross-section shape. This paper also gives an outline of the application of the DPLEX method in the construction of a rectangular (4.2 m x 3.8 m) sewerage tunnel under unusually severe conditions — the small overburden, narrow road, and presence of several embedded structures.

ABSTRAKT: Diese Studie Beschreibt das Prinzip und die Eigenschaften der DPLEX-Schildmethode. Die neue Methode, eine verbesserte Version der EPB-Schildmethode, kann zum Bau von Tunneln mit praktisch jeder beliebigen Querschnittsform verwendet werden. Diese Studie gibt einen Überblick uber die Anwendung der DPLEX-Methode beim Bau eines rechteckigen (4.2m x 3.8m) Kanalisationstunnels unter außergewöhnlich schwierigen Bedingungen — kleine Oberschicht, schmale Straße und Anwesenheit verschiedener eingebetteter Strukturen.

1 INTRODUCTION

In the construction of tunnels in urban areas, where the securing of city functions and the conservation of a good living environment are strong social demands, the shield method has been most widely employed because it meets those demands better than any other method. Most of the tunnels that have been built so far are round in cross section. In recent years, with the expansion of city population, more and more underground structures and building foundations have been constructed. As a result, there is growing demand for a new method which enables tunnels to be excavated efficiently under exceptionally severe conditions. In order to meet the demand, Daiho Corporation has come up with the DPLEX (Developing Parallel Link Excavating) shield method. With this method, it is possible to build tunnels of any cross-section shape — rectangular, oval, horseshoe, circular — according to the tunnel use and excavation conditions.

This paper describes the principle and features of the DPLEX shield method and gives an outline of the construction of extremely close-set rectangular tunnels using the DPLEX shield method.

2 PRINCIPLE AND FEATURES OF THE DPLEX SHIELD METHOD

The DPLEX shield method employs multiple rotating shafts to which cranks are fitted at right angles. A cutter frame equipped with many cutter bits is universally coupled to the ends of the rotating shafts. As the rotating shafts turn, the cutter frame starts a parallel link motion, which makes it possible to cut a tunnel of a cross section analogous to the shape formed by the cutter bits.

The excavating mechanism of the DPLEX shield method applies the motion of the driving wheel and connecting rod of a steam locomotive. As shown in Fig. 1, when the cutter frame (this corresponds to the connecting rod) having many cutter bits is turned, all the cutter bits turn drawing a circular locus with the same radius. The combination of cutter bits permits cutting a tunnel of desired cross-section shape — rectangular, circular, etc. For example, a rectangular formation of cutter bits enables cutting a tunnel of cross section analogous to the shape formed by the cutter bits. The rectangular cross section of the shield is shown in Fig. 2.

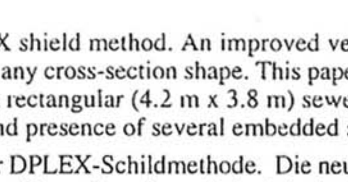


Fig. 1 Principle of cutter frame rotation

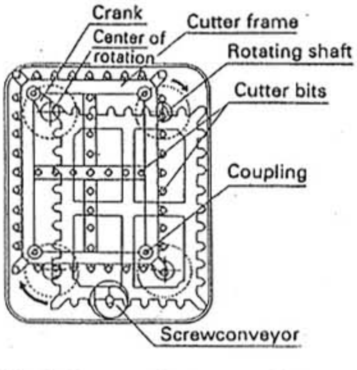


Fig. 2 Rectangular cross section

The cutting face is stabilized by a muddy-soil pressure balancing system. In this system, the mixture of excavated soil and mud-making agent is kneaded into mud having plastic fluidity by the blades at the back of the cutter frame, and then the mud fills the chamber, thereby stabilizing the cutting face. The mud pressure is kept constant during excavation.

The salient features of the DPLEX shield method are as follows.

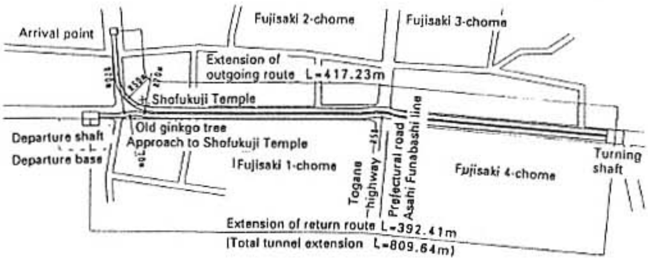


Fig. 3 Plan of the route

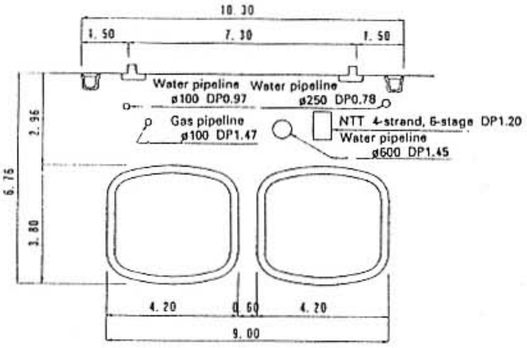


Fig. 4 Cross section of the underground

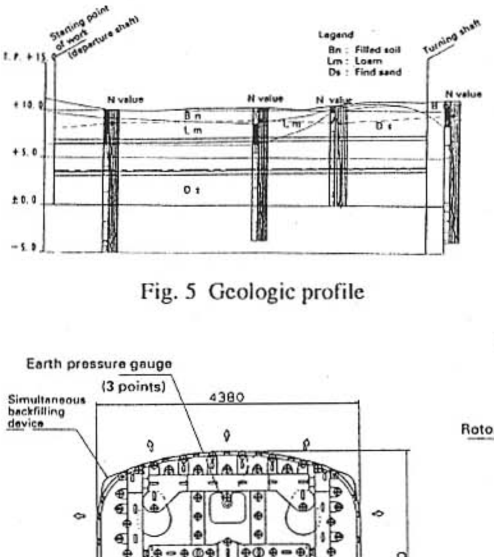


Fig. 5 Geologic profile

(1) By changing the formation of cutter bits, it is possible to cut a tunnel of virtually any cross-section shape.

(2) The DPLEX shield method is widely applicable under diverse underground conditions.

(3) The DPLEX shield method is applicable to various types of soil.

(4) Since the cutter turning radius is small, the torque and power required of the cutter are small.

(5) Because of the small cutter turning radius and the short sliding distance of cutter bits, the cutter hardly wears, allowing for long-distance excavation.

3 OUTLINE OF TUNNEL CONSTRUCTION PROJECT

1) Contents of work

Work name: Kikutagawa No. 2 Trunk Sewerage Tunnel Construction Work 18/22 in Narashino City.

Extension: 392.4 m going, 417.2 m returning (total: 809.6 m).

Tunnel cross section: Rounded rectangle with finished inside dimensions 3400 mm x 2800 mm.

Segment: Outside width 4200 mm x outside height 3800 mm, wall thickness 250 mm (materials: RC and ST).

Shield method: DPLEX.

2) Outline of route

Twin tunnels of natural flow type were planned to be dug under a busy municipal road (minimum width: 10 m) which leads to JR Tsudanuma Station. A municipal water pipeline (600 mm in diameter), NTT cable line, etc. are embedded in the ground above the planned tunnels. The shield reaches an S-shaped curve (R = 70 m) immediately after it starts. There are also several sharp curves (R = 58 m, 50 m, etc.) along the way. Since the distance between the two rectangular tunnels is only 600 mm, the terminal of the return tunnel is connected to an existing tunnel. The plan of the route is shown in Fig. 3, and the cross section of the underground is shown in Fig. 4.

3) Geological features

The soil of the tunnel construction site consists mainly of fine sand, though the Kanto loam is partly found in layers above the tunnels. The ground around the terminal consists of weak silt and humus soil. The geologic profile of the project site is shown in Fig. 5.

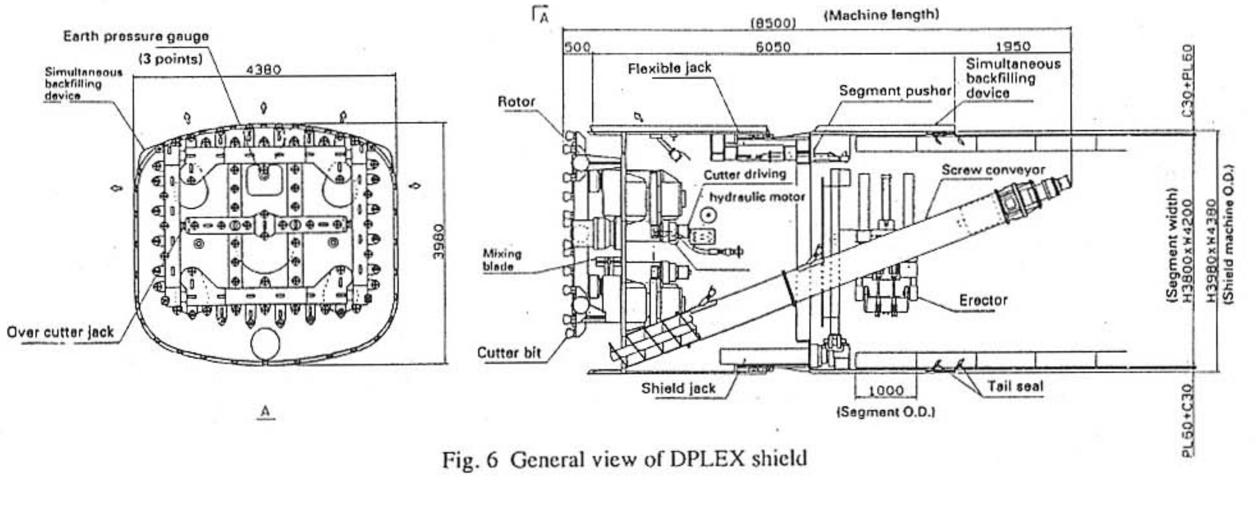


Fig. 6 General view of DPLEX shield

4) Major specifications of the shield

Shield outside diameter: 4380 mm wide x 3980 mm high.

Shield overall length: 8500 mm (machine length: 6050 mm).

Total thrust: 1780 tf.
Shield jacks: 120 tf x 9, 100 tf x 7.
Flexible jacks: 120 tf x 12.
Screwconveyor: 470 mm in diameter.
Cutter driving system: Hydraulic.
Cutter torque: 88.4 tf-m (22.1 tf-m x 4).
Cutter turning radius: 300 mm.
Cutter rotating speed: Max. 4 rpm.

4 WORK REPORT

1) Mud pressure control

Along the return route, the controlled mud pressure was initially set in the range 0.7 to 1.3 kgf/cm^2 taking into consideration the effects of the overburden, groundwater, and nearness to the adjoining tunnel. Since the effect of the return tunnel on the adjoining tunnel was found small during the actual excavation work, the low limit of mud pressure was raised to 0.8 kgf/cm^2 (the high limit was kept unchanged at 1.3 kgf/cm^2) to reduce the variance in mud pressure. The change in mud pressure in the chamber is shown in Fig. 7.

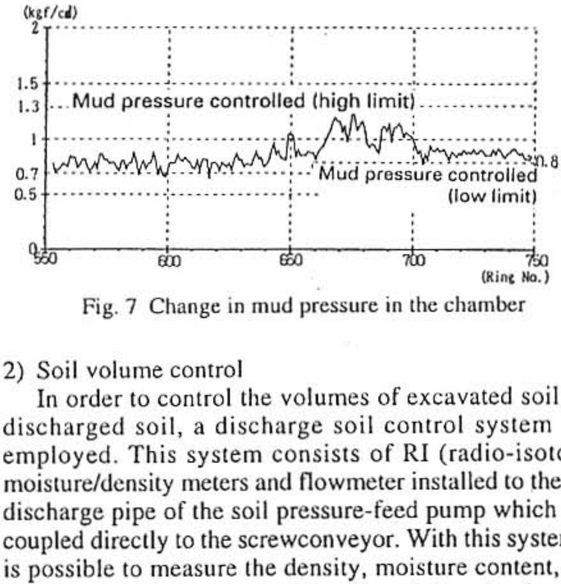


Fig. 7 Change in mud pressure in the chamber

2) Soil volume control

In order to control the volumes of excavated soil and discharged soil, a discharge soil control system was employed. This system consists of RI (radio-isotope) moisture/density meters and flowmeter installed to the soil discharge pipe of the soil pressure-feed pump which was coupled directly to the screwconveyor. With this system, it is possible to measure the density, moisture content, and volume of discharged soil on a real-time basis. The measured density and moisture content of discharged soil are shown in Figs. 8 and 9. The density of discharged fine sand was 1.9 to 1.95 tf/m^3 — nearly the same as the unit weight of the natural ground obtained during boring test. With respect to the volume of discharged soil, the volume calculated from the piston speed of the pressure-feed pump was almost equal to the sum of the volume of excavated soil and the volume of mud-making agent.

3) Ground disturbance

During excavation of the outgoing tunnel, the leading ground subsidence was minimal. The ground rose about 5 mm when the machine came right under, then subsided about 5 mm when the machine passed through. During excavation of the return tunnel too, the trailing ground subsidence at the shield center was not more than about 10 mm. Thus, the excavation of the tunnels had minimal effect on the residential houses, etc. in the locality. The results of measurement of ground disturbance are shown in Fig. 10.

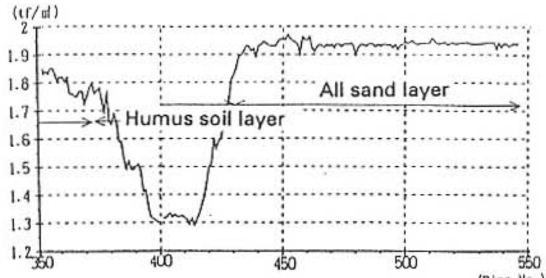


Fig. 8 Change in density of discharged soil

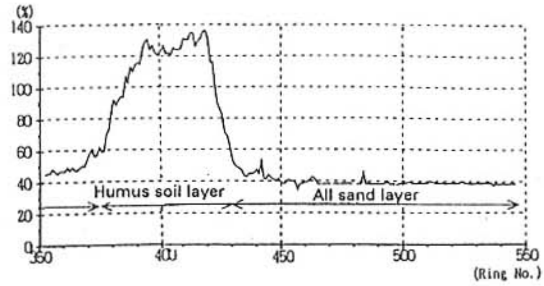


Fig. 9 Change in moisture content of discharged soil

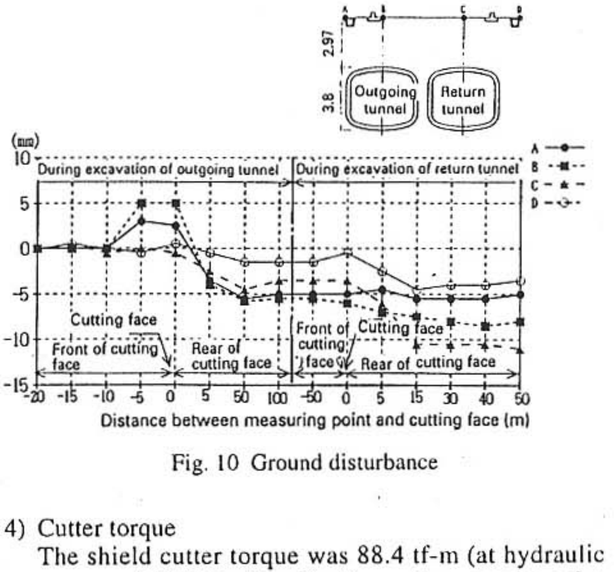


Fig. 10 Ground disturbance

4) Cutter torque

The shield cutter torque was 88.4 tf-m (at hydraulic pressure of 210 kgf/cm^2). From the results of a demonstrative test, a torque coefficient of about 1.0 for an equivalent round cross section (4.5 m in diameter) was used.

The cutter hydraulic pressure during excavation of a sand layer was 40 to 60 kgf/cm^2 ($\alpha = 0.25$ to 0.3), that is, about 1/5 to 1/4 of the installed torque. In the neighborhood of the 700th ring in the humus soil layer, it was about 30 kgf/cm^2 ($\alpha = 0.14$), or about 1/7 of the installed torque. Thus, compared with the conventional single-shaft cylindrical shield, the torque required for excavation could be reduced to 1/4 to 1/3. The change in cutter hydraulic pressure is shown in Fig. 11.

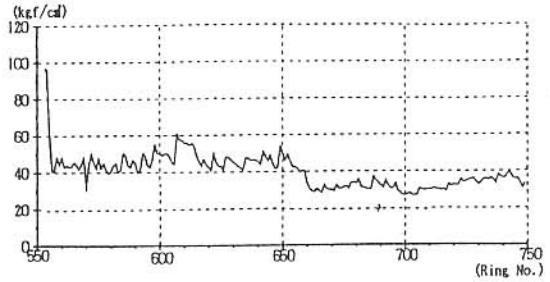


Fig. 11 Change in cutter hydraulic pressure

5) Shield jack thrust

The shield jack thrust was 850 tf at maximum, 600 tf on average, and 25 to 50 tf/m² per unit area. The change in jack thrust during excavation is shown in Fig. 12.

6) Excavation speed

The excavation speed was 30 to 35 mm per minute, which is comparable to the excavation speed for a circular tunnel by an earth pressure shield.

7) Rolling

The tolerable rolling during excavation of one ring (1 m) is ±0.6 degree. In the actual excavation work, however, the rolling was controlled to ±0.3 degree.

The degree of rolling that actually occurred was less than the control value, and the cumulative rolling was about 0.6 degree at most. The rolling that did occur could be corrected easily by an exclusive jack. The change in rolling during excavation is shown in Fig. 13.

8) Segment measurement

The soil pressure, water pressure, backfilling pressure, reinforcing bar stress, etc. acting upon the segment were measured by the instruments shown in Fig. 14. Those measuring instruments were installed in rings 525 and 526 near the terminal of the outgoing tunnel (28 m from the turning shaft) (see Fig. 15). The effect of backfilling pressure on the segment during excavation of the outgoing tunnel was measured. In addition, the effects of excavated soil pressure and backfilling pressure on the outgoing segment during excavation of the return tunnel were measured since the two tunnels are close-set.

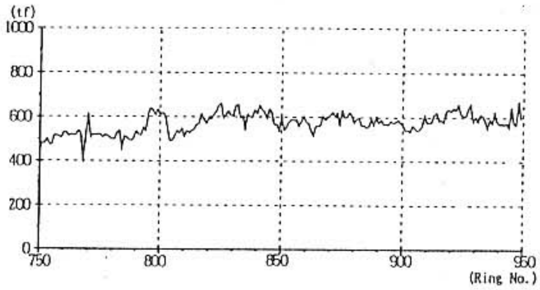


Fig. 12 Change in jack thrust

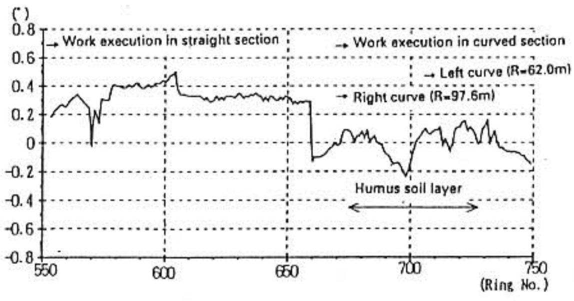


Fig. 13 Change in rolling

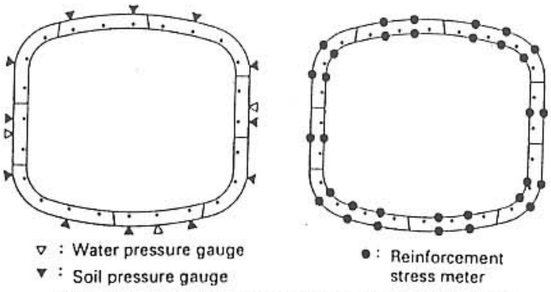


Fig. 14 Arrangement of measuring instruments

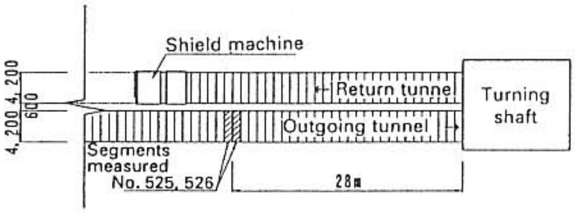
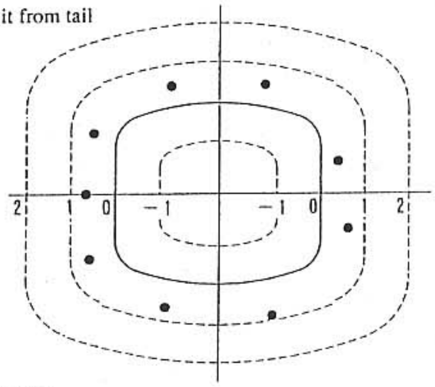


Fig. 15 Location of segments measured

During exit from tail



One month later

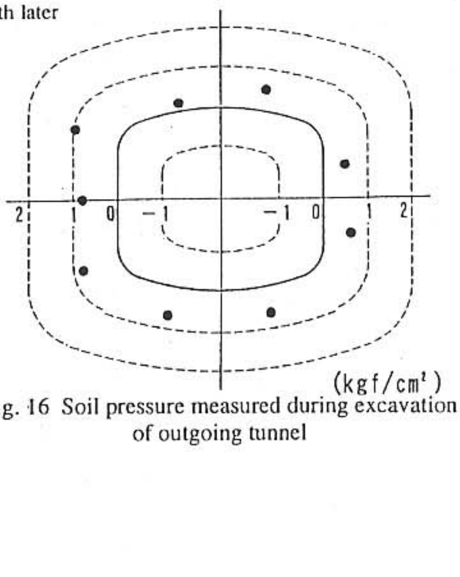


Fig. 16 Soil pressure measured during excavation of outgoing tunnel

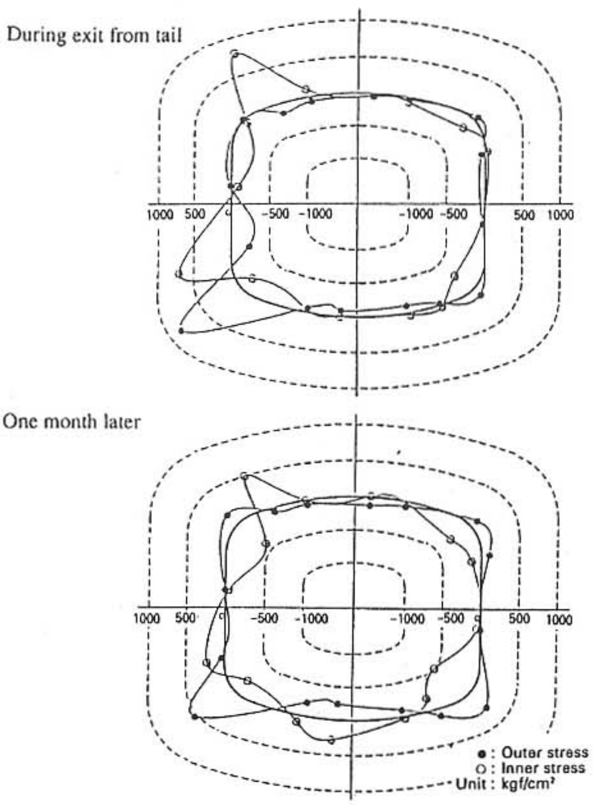


Fig. 17 Reinforcement stress measured during excavation of outgoing tunnel

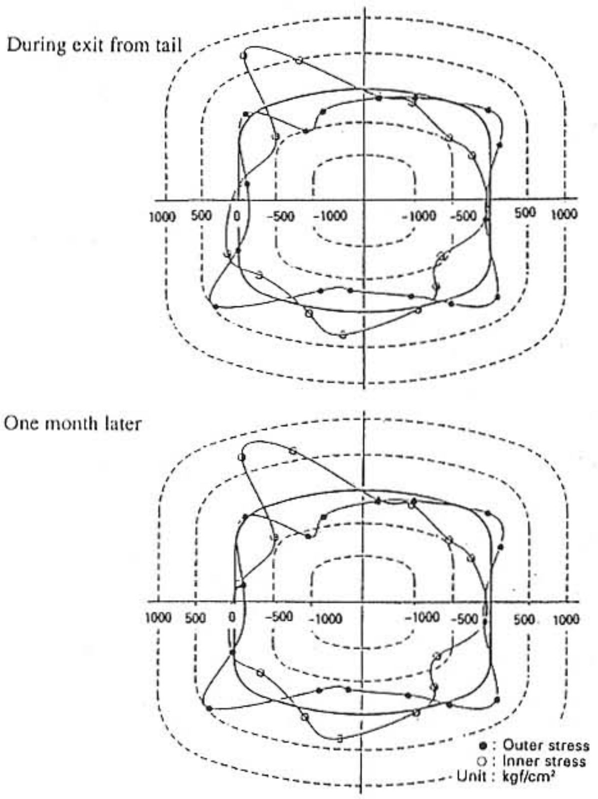


Fig. 18 Reinforcement stress measured during excavation of return tunnel

(1) Soil pressure gauge/water pressure gauge

During exit from the tail of the outgoing tunnel, the soil pressure gauge indicated 0.4 to 1.0 kgf/cm² due to the influence of backfilling pressure. One month later, due to the influence of the soil and water pressures from the surrounding natural ground, the soil top pressure decreased and the lateral soil pressure increased by 0.1 to 0.5 kgf/cm². The increase in lateral soil pressure is considered due to a ground reaction caused by a deformation of the segment under the load of natural ground. Nearly the same results were obtained during excavation of the return tunnel.

The water pressure gauge indicated about 0.5 kgf/cm² at the bottom of the segment. It was almost equal to the value estimated from the level of groundwater. The soil pressure measured when the tail of the outgoing shield passed through and the soil pressure measured one month after that are shown in Fig. 16.

(2) Reinforcing bar stress meter

While the tail of the outgoing shield was passing, the stress gauges on the segment outer and inner surfaces showed a maximum tensile stress of 860 kgf/cm² and 810 kgf/cm², respectively, due to the effect of backfilling pressure. Once month later, the maximum tensile stress decreased to approximately 500 kgf/cm² as the backfill hardened.

While the tail of the returning shield was passing, the stress gauges on the segment inner surface showed a maximum tensile stress of 730 kgf/cm² due to the effect of backfill on the two tunnels. Even one month after the shield passed, the maximum tensile stress at the segment inner surface remained nearly the same. The reinforcement stresses in outgoing segments measured during excavation of the outgoing tunnel and return tunnel, respectively, are shown in Figs. 17 and 18.

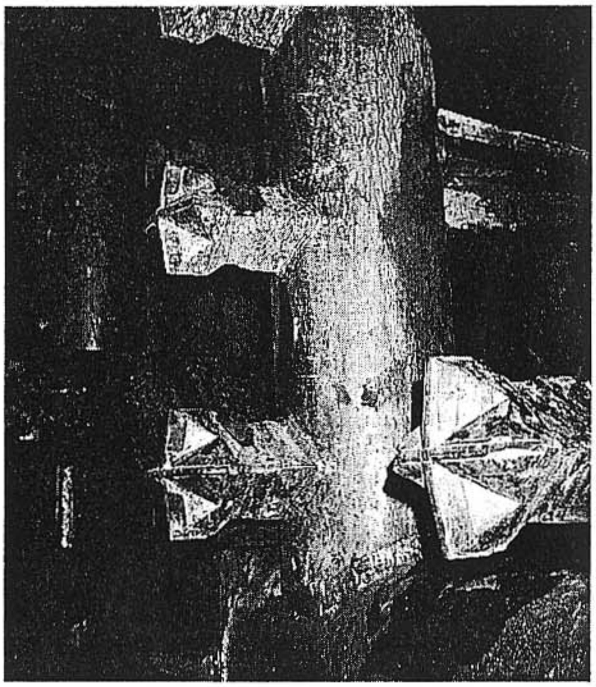


Photo 1 Condition of cutter bit wear after excavation

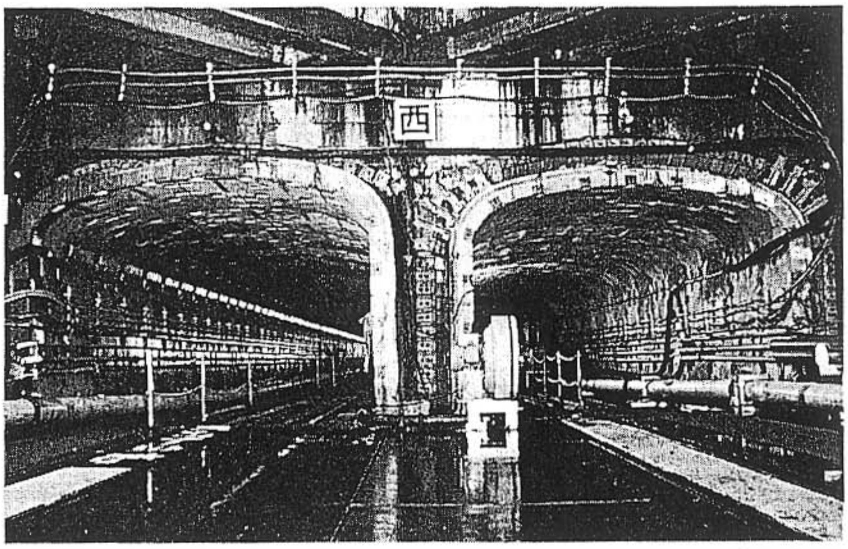


Photo 2 Primary linings of outgoing and return tunnel

From the above results, it can be seen that the corners and top reinforcing bars of the outgoing segments are influenced by the passing of the shield during excavation of the return tunnel. In particular, the position and pressure of simultaneous backfilling have significant effect on the reinforcement stress.

9) Measurement of cutter bit wear

Since the turning radius of the DPLEX shield cutter is small, the sliding distance of the cutter bits is uniform and short — about 1/3 of the sliding distance of the outermost part of the single-shaft round shield.

Therefore, the amount of wear of cutter bits was estimated to be smaller. At the end of excavation of the tunnels, the amount of wear of the cutter bits was measured.

The measured wear over the entire excavation section (mostly Narita sand layer) was 1.85 mm on average. Since the total sliding distance of the cutter was about 205 km, the coefficient of wear, or the amount of wear per unit sliding distance, was 0.009 mm/km. The condition of cutter bit wear is shown in Photo 1.

With conventional round shields, the coefficient of wear is approximately 0.01 to 0.02 mm/km in sand layer. Thus, the amount of wear of cutter bits of the DPLEX shield is smaller. From the sliding distance and wear coefficient of the cutter bits of the DPLEX shield, it is considered possible for the DPLEX shield to excavate three to four times longer than the conventional round shield.

5 CONCLUSION

Despite unusually severe conditions of the present work – the small overburden, excavation of close-set twin tunnels, and presence of sharp curves, the primary and secondary linings could be completed successfully. The present achievements and the principle of excavation suggest that the advantages of the DPLEX shield should be able to be incorporated in the conventional round shield. In particular, when the DPLEX method is applied to large-diameter shields for long-distance excavation, significant effect could be obtained. In view of this, we intend to further promote the research and development in the future.

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