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Development of a prestressed and precast concrete segmental lining

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Abstract

Prestressed & precast concrete segmental lining (P&PCSL) is used for shield tunnels. Its primary feature is that it integrates segments into one ring by introducing prestress in the tunnel circumferential and longitudinal directions. Introducing prestress enables the elimination of bolt joints and reduces the volume of reinforcement, thus reducing the manufacturing cost of precast concrete segments. It also enables quality improvement and labor saving in lining and provides greater adaptability for tunnels with large diameter, where deformation due to dead load is a problem. The P&PCSL has been implemented in three construction projects after undergoing various performance tests and workability verification tests.

Keywords: Shield tunnel; Prestressed concrete; Segmental lining; Performance tests; Building verification tests

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1. Introduction to P&PC segmental lining

1.1. Outline of the method

The P&PCSL provides a lining ring of post-tensioned prestressed concrete structure by assembling a concrete ring segmented, giving it tension, and fastening it by inserting a prestressing single strand into the sheath that is preliminarily embedded in the precast concrete segment (Fig. 1).

Because an unbonded prestressing strand with low friction loss between a prestressing steel and a sheath, is used for the prestressing strand, sufficient prestress can be introduced if tension is applied to only one position on the whole circumference (Fig. 2). Furthermore, by using a combined anchoring device made of cast iron that has the tension side and fixing side integrated into one piece (X anchor) by embedding it in the segment, the reinforcement in the segment can be simplified and workability of tensioning can be improved (Fig. 3).

A system in which a segment can be pressed against and contacted to an existing segment by using shield jacks is used to assemble segments; no bolt joints are used between rings or between segments.

In order to improve the lining durability, the high viscous grouting is injected into the gap between the unbonded prestressing strand and the sheath made of polyethylene. The boxing-out for tensioning work is also treated by the non-shrinkage mortar as the concrete surface finish for completion.

1.2. P&PC segmental lining features

1.2.1. Economic efficiency

Because segments are integrated into one piece by introducing prestress, joint metals can be eliminated. Also, the volume of reinforcement to obtain the same bending performance can be reduced largely as compared with conventional reinforced concrete structures. Furthermore, the depth of the segmental lining can also be reduced in segments with a medium to large aperture. Owing to these features, the segment manufacturing cost can also be reduced. In addition, this segment can eliminate secondary concrete lining, so a total cost reduction can be achieved by reducing the outer diameter of the tunnel.

1.2.2. Quality

Cracking in the concrete can be suppressed by introducing prestress. Furthermore, a segment that has excellent smoothness and water-tightness with small

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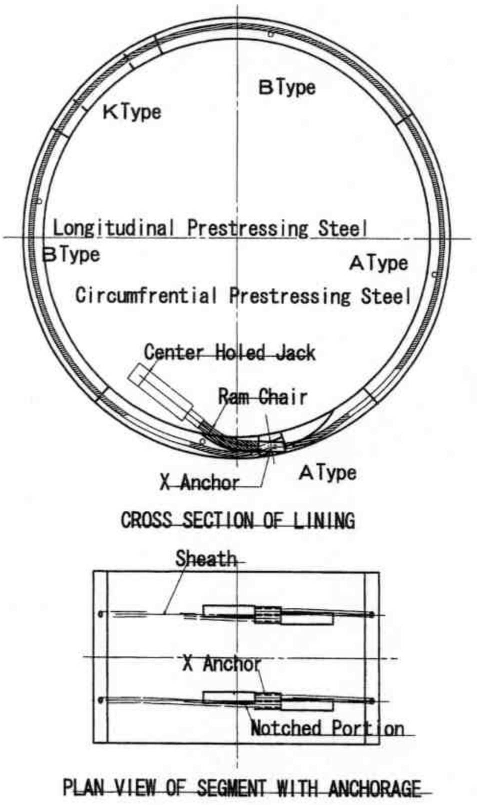

Fig. 1. P&PC segmental lining.

deformation of the lining ring during building can be achieved because radial joint gaps and steps are very small. Moreover, as an unbonded prestressed concrete structure, it is tough with a high stability, and joints are resistant against breakage even under a high load. In the tunnel longitudinal direction, in particular, such flexibility helps to improve anti-seismic durability.

1.2.3. Buildability

Segments are built without any bolts; only fastening with shield jacks is required. As a result, buildability can be improved and automatic lining operation can be easily implemented. Furthermore, tensioning in the tunnel circumferential direction is applied at only one point of the whole circumference, so buildability can be improved with little influence on the construction cycle time.

1.2.4. Smooth intrados

The segment has an intrados with minimal roughness and no metal on the surface. It has high water-tightness, and cracking can be suppressed by prestressing.

It is thus suitable for single-pass structure without secondary concrete lining.

1.2.5. Resistance against internal pressure

For tunnels subjected to high internal water pressure, concrete can be held in a fully compressed state by introducing prestress, ensuring stability and water-tightness.

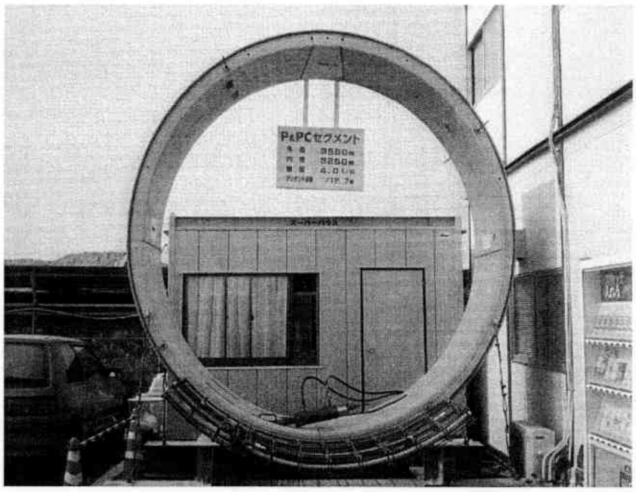

Fig. 2. P&PC segmental lining (photo).

2. Outline of experiments on P&PC segmental lining

2.1. Summary

We performed various tests on the P&PCSL while developing it to confirm the basic performance and buildability of those segments where prestress is introduced in the tunnel circumferential and longitudinal directions (Nishikawa et al., 1997). The results of these various tests are summarized in Table 1. For instance, the results of bending tests on segment joints, where features of the structure of the P&PCSL is clearly shown, are reported in this section, as follows.

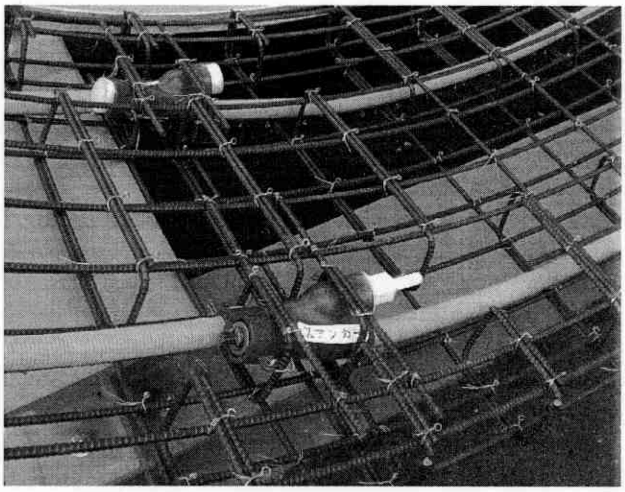

Fig. 3. X anchor.

Table 1
Basic performance tests

Outer diameter of 2400 mm Basic performance verification test	Circumferential and longitudinal tensioning tests Joint performance test Rigidity/durability tests
Outer diameter of 2950 mm Basic performance verification test	Single-unit bending and joint Bending tests Ring loading test Jack thrusting and hanger metal Pulling test
Outer diameter of 2950 mm Workability verification test	PC grouting test Segment assembling test
Outer diameter of 2700 mm Basic performance verification test	Internal water pressure loading test
Outer diameter of 3550 mm Basic performance verification test	Single-unit bending and joint Bending tests Jack thrusting and hanger metal Pulling test
Outer diameter of 3550 mm Workability verification test	Segment assembling test

2.2. Bending test on segment joints

2.2.1. Outline of the test

We performed a bending test on segment joints by applying prestress to the arch-formed beam jointing two A-type segments (using two prestressing strands) and applying concentrated loads to this specimen supported by two points at both ends (Figs. 4 and 5). The load applied, horizontal and vertical displacements, tensile force, surface strain of concrete, and joint gaps were measured. Test procedures are shown in Table 2.

2.2.2. Test results

A load was applied until the joint broke under a load of $P_{max} = 37.1$ kN: the load was then removed. The design bending strength Pj2 using an unbonded pres-

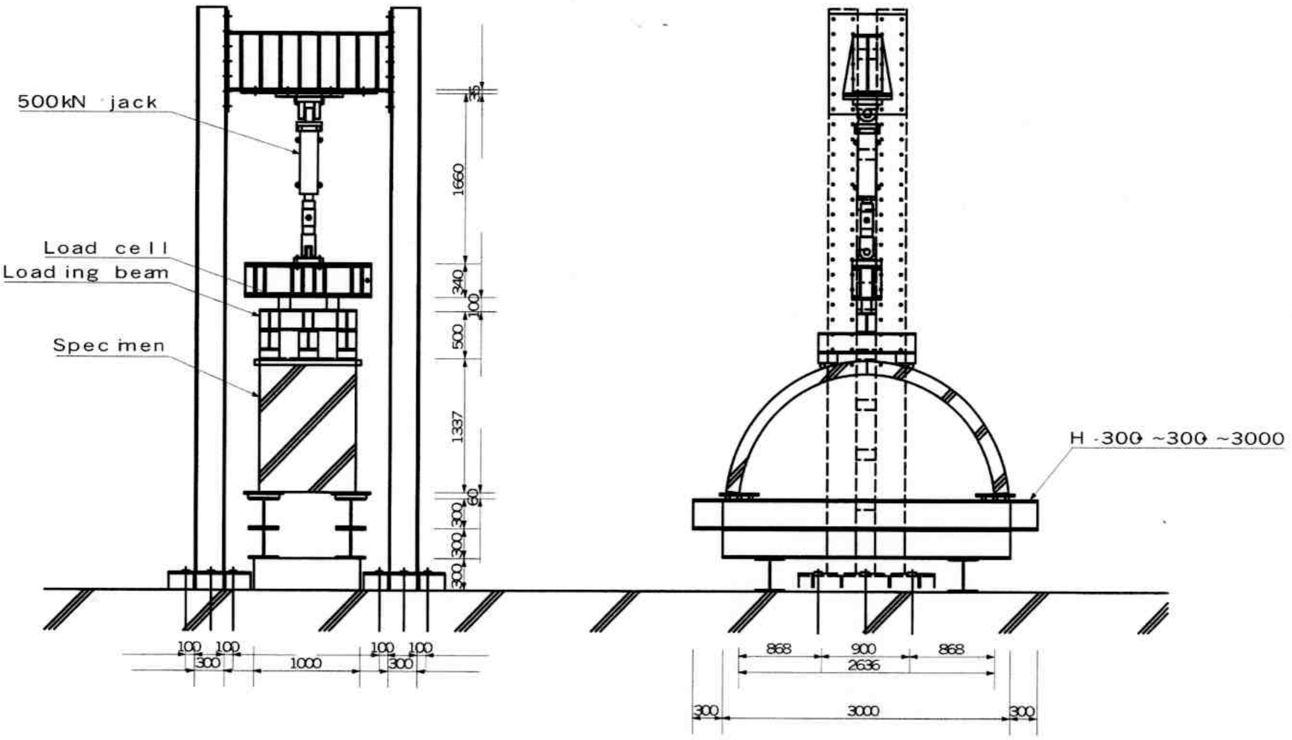

Fig. 4. Bending test of joint.

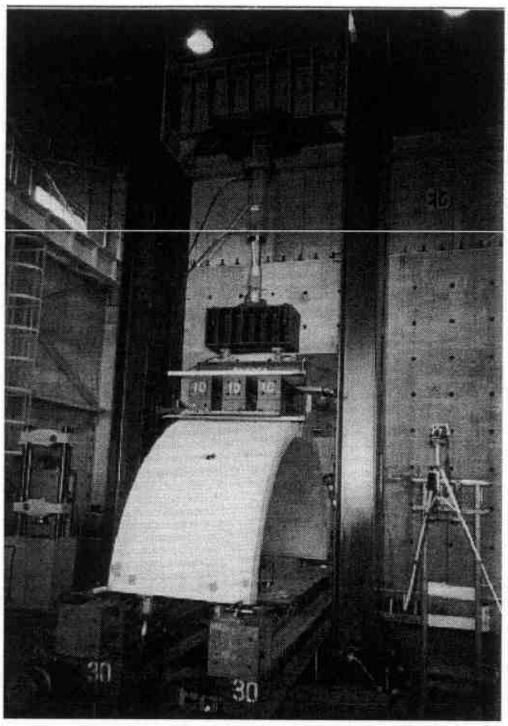

Fig. 5. Bending test of joint (photo).

Table 2
Example of test procedures

Tensioning force introduced	86.3 kN per strand
Resisting moment of joints	10.8 kN-m
Breaking moment of joints	17.0 kN-m
Distance between loading points	900 mm
Distance between supports	2653.5 mm
Breaking load of joints (Pj2)	29.4 kN

tressing single strand is 29.4 kN, confirming a sufficient bending strength. Furthermore, the horizontal displacement was restored to the initial state before loading (0 mm) when the load was reduced to 0 kN because prestress is introduced, confirming that an unbonded structure has high stability (Fig. 6). The rotation spring constant of segment joints was greater than that calculated using the empirical formula of Leonault and Reimann (1966) (Fig. 7).

3. Construction in site

3.1. Outline of work

After undergoing various performance verification tests and workability verification tests, the P&PCSL was adopted to three sewage construction works (Saito et al., 1999). One of them is clearly reported in this section. Table 3 summarizes the work contents.

3.2. Working conditions

Overburden above the shield is 10–11 m, with the soil in the shield excavation section consisting of a basic layer of alluvium with a water content of 59% and the unconfined compressive strength of 0.12 N/mm^2.

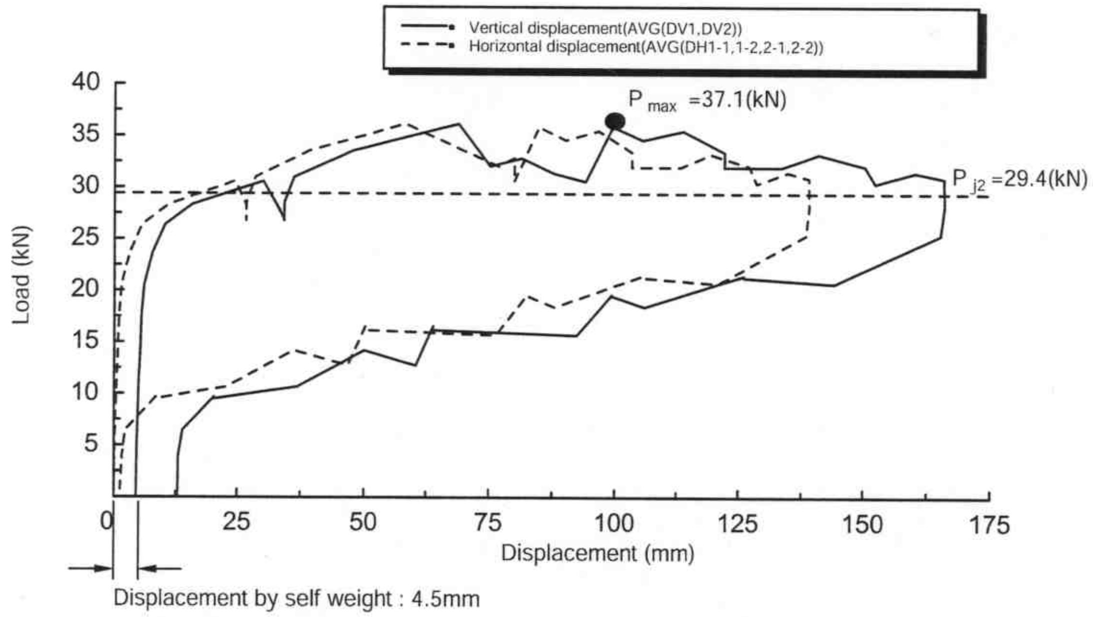

Fig. 6. Load vs. displacement curves.

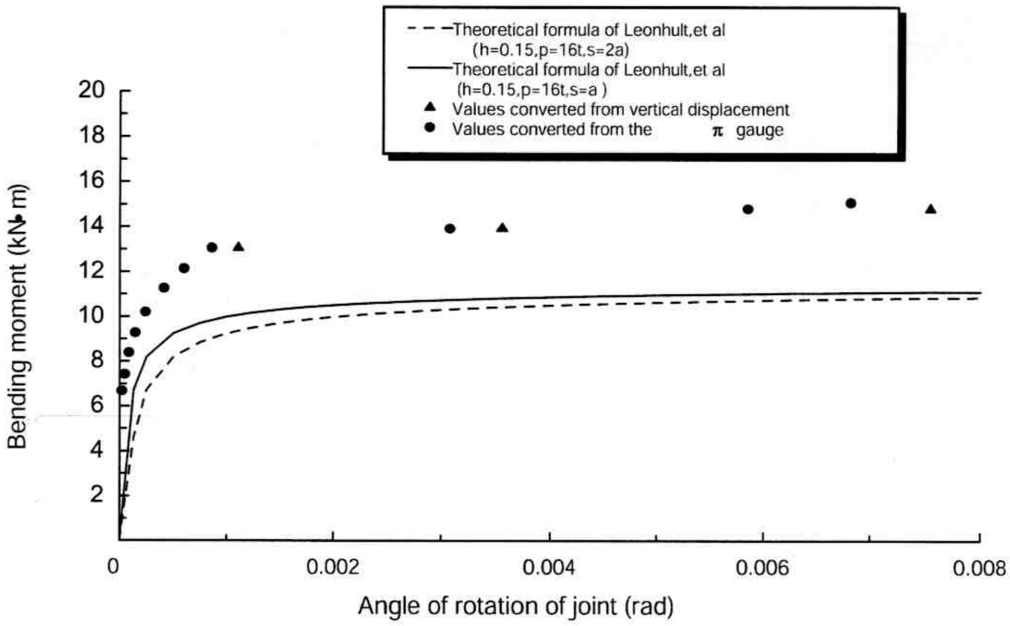

Fig. 7. Bending moment and rotating angle.

In the stage of planning, the alignment consists of the straight section having a length of 204 m and the curved section having a length of 14 m with a radius of 1000 m (Fig. 8). The gradient is 0.9% upward, where excavation was made while climbing the slope.

3.3. P&PC segmental lining

The major specifications of the P&PCSL used for this project are shown in Table 4. Delivered segments are temporarily stocked on site (Fig. 9).

3.4. Shield machine

Table 5 summarizes the specifications of the shield machine used. A boltless building method is applied when the P&PCSL is used, so temporary support jacks are installed at the top of the shield tail (Figs. 10 and 11). The rest of the mechanism is the same as that of the shield machine used for conventional precast concrete segmental lining bolted.

Table 3
Example of test procedures

Tensioning force introduced	86.3 kN per strand
Resisting moment of joints	10.8 kN-m
Breaking moment of joints	17.0 kN-m
Distance between loading points	900 mm
Distance between supports	2653.5 mm
Breaking load of joints (Pj2)	29.4 kN

3.5. Construction results

3.5.1. Buildability of assembling the P&PCSL

To build the P&PC lining segments, a system in which segments are built by pressing a new segment against the existing segment in turn using shield jacks was adopted (Fig. 12). A new segment was easily aligned with the existing segment by matching the marks provided in the tunnel longitudinal sheath position. Temporary support jacks were used as auxiliary tools to secure sufficient safety after the upper segments were fastened by using a shield jack (Fig. 13).

3.5.2. Inserting, tensioning, and fastening unbonded prestressing strands

An unbonded prestressing single strand was inserted by a worker pushing in manually (Fig. 14). To tension unbonded prestressing strands, the required tensile force was firstly introduced, and then the tensioning jack was released so that the wedge was pulled in to fasten the strand (Fig. 15).

3.5.3. Results of on-site measurement

Prestress was measured in the tunnel circumferential and longitudinal directions using a concrete strain gauge and load cell at an intermediate point within the range of total of 204 rings. The loss of prestress due to anchorage set was 39.2 kN as the calculated value (Fig. 16). The reduction of prestress was only 1% of the prestress just after tensioning when 110 days had passed since the completion.

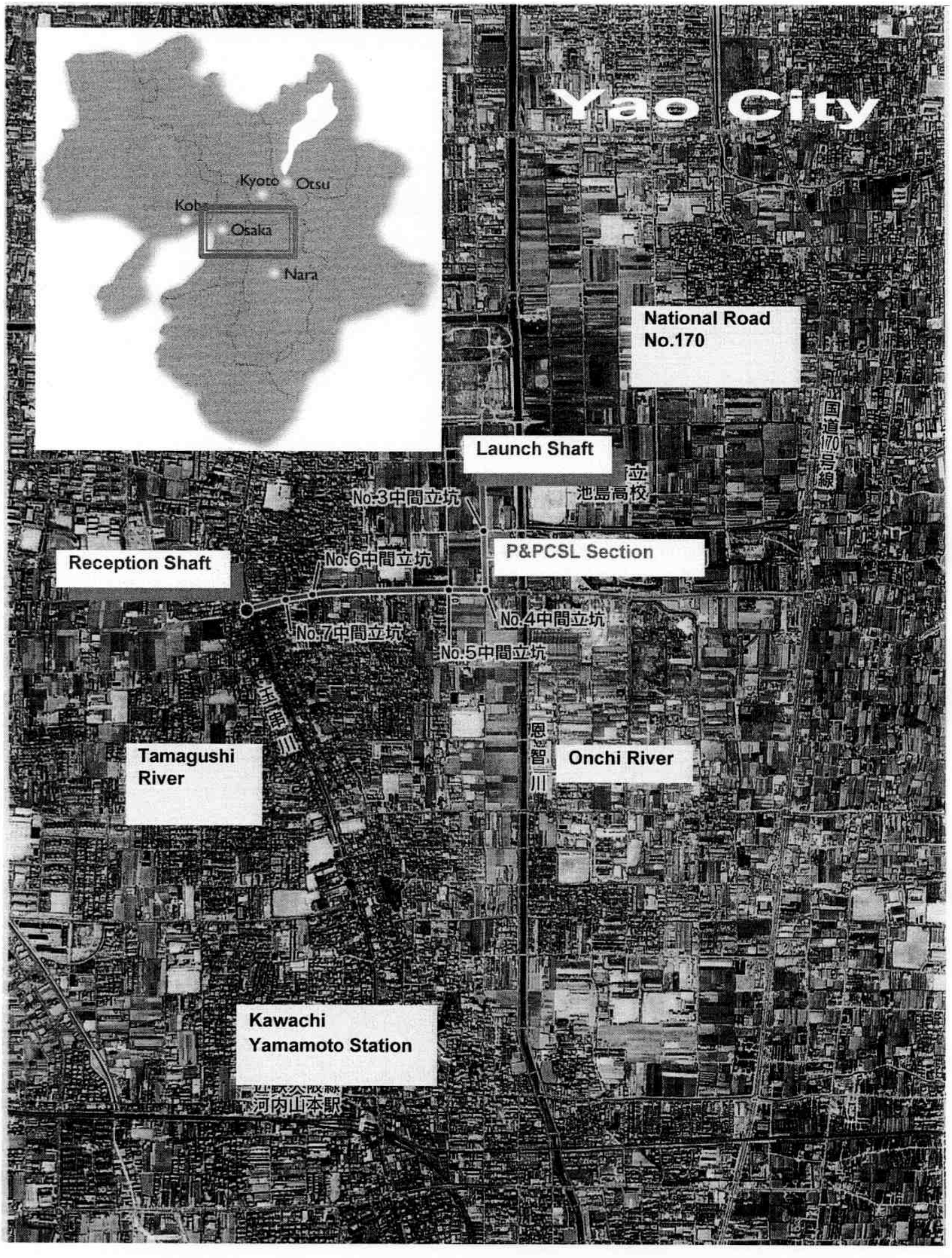

Fig. 8. Plan of work section.

Table 4
Major specifications of the P&PCSL

Form	Outer diameter 3550 mm Depth 150 mm Width 1000 mm
Division	4 segments plus 1 key
Tensioning material (/ring)	Unbonded prestressing single strand (1T-12.7 mm). 2 nos. for circumferential direction 4 nos. for longitudinal direction
Concrete reinforcing bar	F'ck = 50 N/mm^2 10 mm dia. 10 nos.
Circumferential joint	Prestress with jointing of flat faces
Longitudinal joint	Prestress with a concrete key at the centre of the joint

Fig. 9. Temporary placement.

3.5.4. Work progress

On the construction cycle time, it took average 25 min to excavate and 40 min to line for the 1 m wide ring. Workers needed 1 week to acquire the new skill. After that, the work progress could achieve 12 m/day on average and a maximum advance of 16 m in 1 day. The target of average advance in the contract is 10 m/day, while 12 m/day is the actual result at the completion of 204 m in this section.

Table 5
Major specifications of the shield

Type of shield machine	Earth pressure balanced shield
Outer diameter	3690 mm
Length	5900 mm
Thrust force	12 MN
Cutter support	Centre shaft system
Screw conveyor	With shaft 470 mm dia.
Segment erector	Rotating ring type 1.5 rev./min
Mucking capacity	47 m^3/h

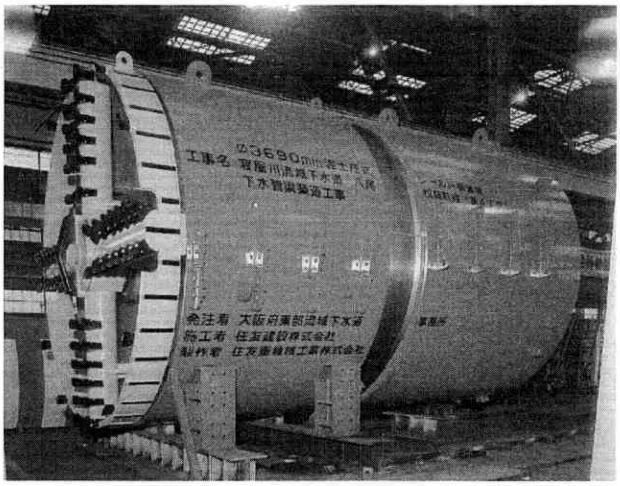

Fig. 10. Earth pressure balanced shield.

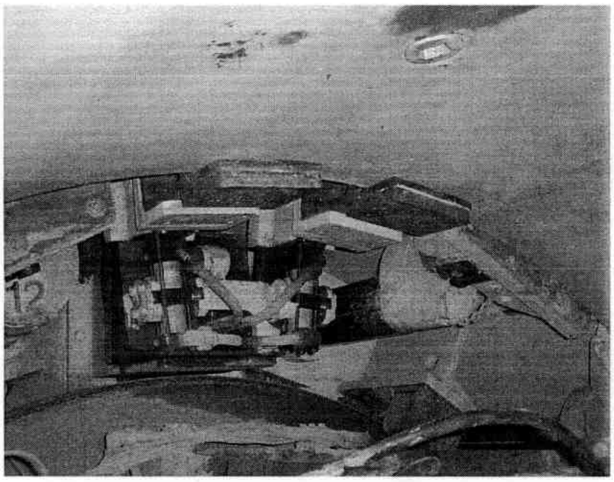

Fig. 11. Temporary support jack.

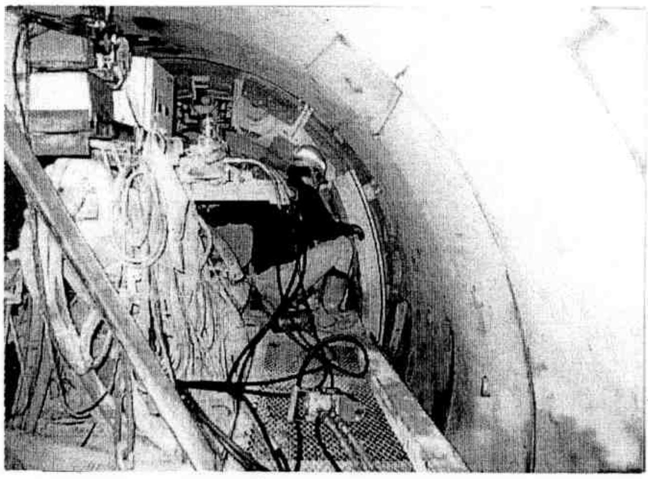

Fig. 12. Building side segment.

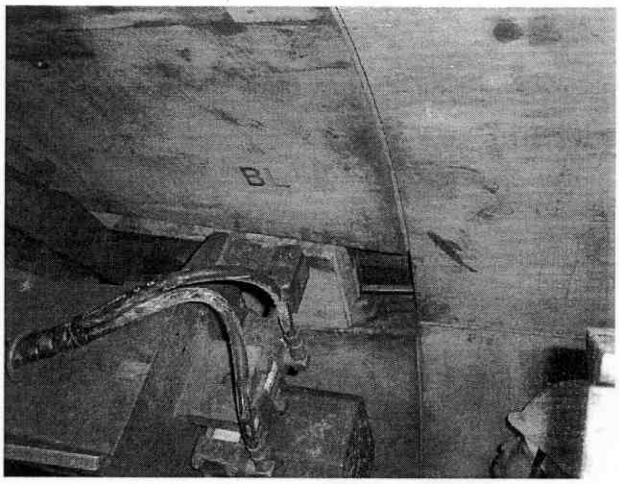

Fig. 13. Building key segment.

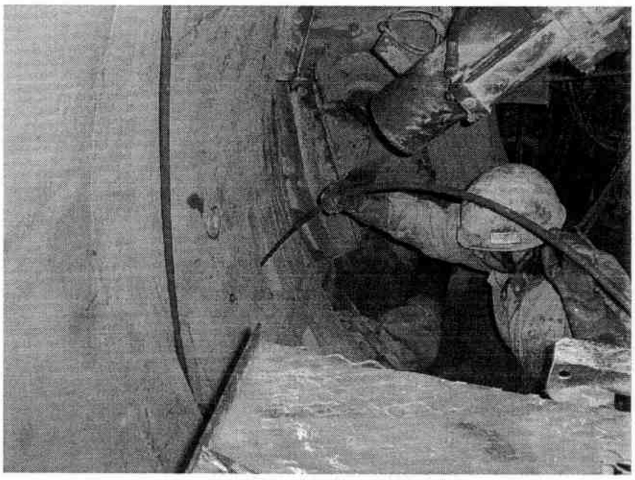

Fig. 14. Inserting prestressing strand.

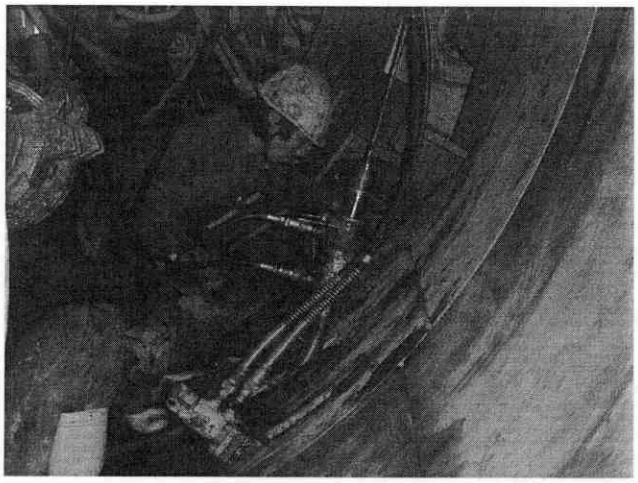

Fig. 15. Circumferential tensioning.

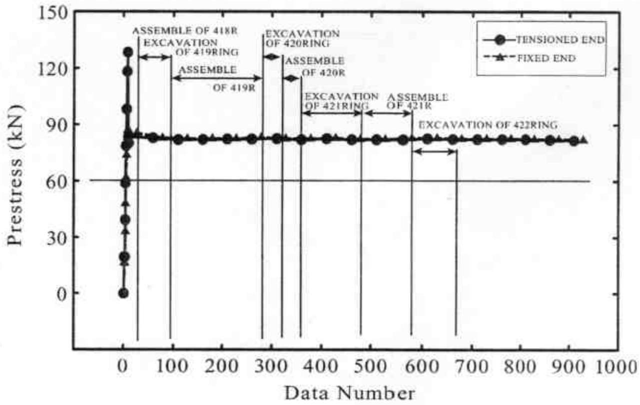

Fig. 16. Trend of circumferential prestressing force.

Fig. 17. Overall view of inside of tunnel.

4. Conclusion

Because the P&PCSL uses prestress, it is more suitable for tunnels with a medium to large span, which are largely structurally affected by the dead load, tunnels exposed to internal pressure, and tunnels with no secondary concrete lining (Fig. 17). We can thus expect the segment to be applied more widely in the future. We intend to further rationalize its workability by accumulating achievements.

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