Planning for shield driven double track subway tunnel of box shape

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ABSTRACT: Construction has commenced on the world's first shield driven double track subway tunnel of rectangular shape for the Kyoto Municipal Subway. Full-scale loading tests were performed on lining segments to confirm the adequacy of their design. Also, as a method by which a rectangular cross section can be excavated, manufacturing is in progress on a "Wagging Cutter Shield," which is equipped with rotating cutters that perform oscillating movement. This paper presents a report on the overall planning and the tests that were performed in the process of planning.

1 INTRODUCTION

The construction of subways is subject to various restrictions due to the fact that they use the space beneath streets, which is public space. At Rokujizo Station, the terminal station on the Kyoto Municipal Subway Tozai Line, the problem was how to shorten the length of cut-and-cover excavation for the station and crossover sections which total 360m. Considering the street width (15m), the required depth of cover (equal to or greater than the outside diameter of the tunnel), and large underground buried structures, a shield driven tunnel of double track cross section of rectangular shape, which is more advantageous than one of multiple circular shape or circular shape, was adopted.

The lining of this shield driven tunnel has an outside width of 9900mm and an outside height of 6500mm. The crossover section, which does not have center pillars, extends for 56m, and the running track section, which does have pillars, extends for 697m. The crossover section was at first thought of as a cut-and-cover section.

Because of the unprecedented scale, and the fact that tunnel linings which have differing modes of deformation will be connected, various preconstruction studies and confirmatory demonstration tests were performed.

2 BASIC PLANNING

The flow of plan determination is shown in Figure 1. The construction site is located in the southeast section of the city of Kyoto, in the southern part of the Yamashina Basin which lies on the eastern side of the Kyoto Basin. In terms of government administration, the site extends from Fushimi Ward of Kyoto into the neighboring city of Uji. An outline of the project is shown in Table 1.

3 DESIGN OF RECTANGULAR SHAPE LINING

3.1 Site conditions

In rising order from the paleozoic basement rock, the soil profile at the site consists of lower diluvial beds (Osaka Group), upper diluvial beds (terrace deposits) and alluvium (including fill). The tunnel will pass through gravel (N-value ranging from 20 to over 50, chiefly medium to small gravel) of the upper diluvial beds for its entire length with a depth of cover of 8.2 to 14.4m. The groundwater level ranges from GL -2.0 to -5.0m

Table 1. Outline of project.

Project name	Kyoto Subway Tozai Line Rokujizo-Kita Construction Section
Location	23-1, Rokujizo Nara-machi, Uji City to 27-4, Ishidamori Higashi-machi, Fushimi-ku, Kyoto City
Owner	Kyoto Municipal Transportation Bureau
Contractor	Kajima Okumura Daiho Yoshimura Okano Construction JV
Construction period	October 1, 1999 to October 31, 2003
Principal structures	Crossover section and running track section, L = 753m
	Launching shaft and driving base shaft

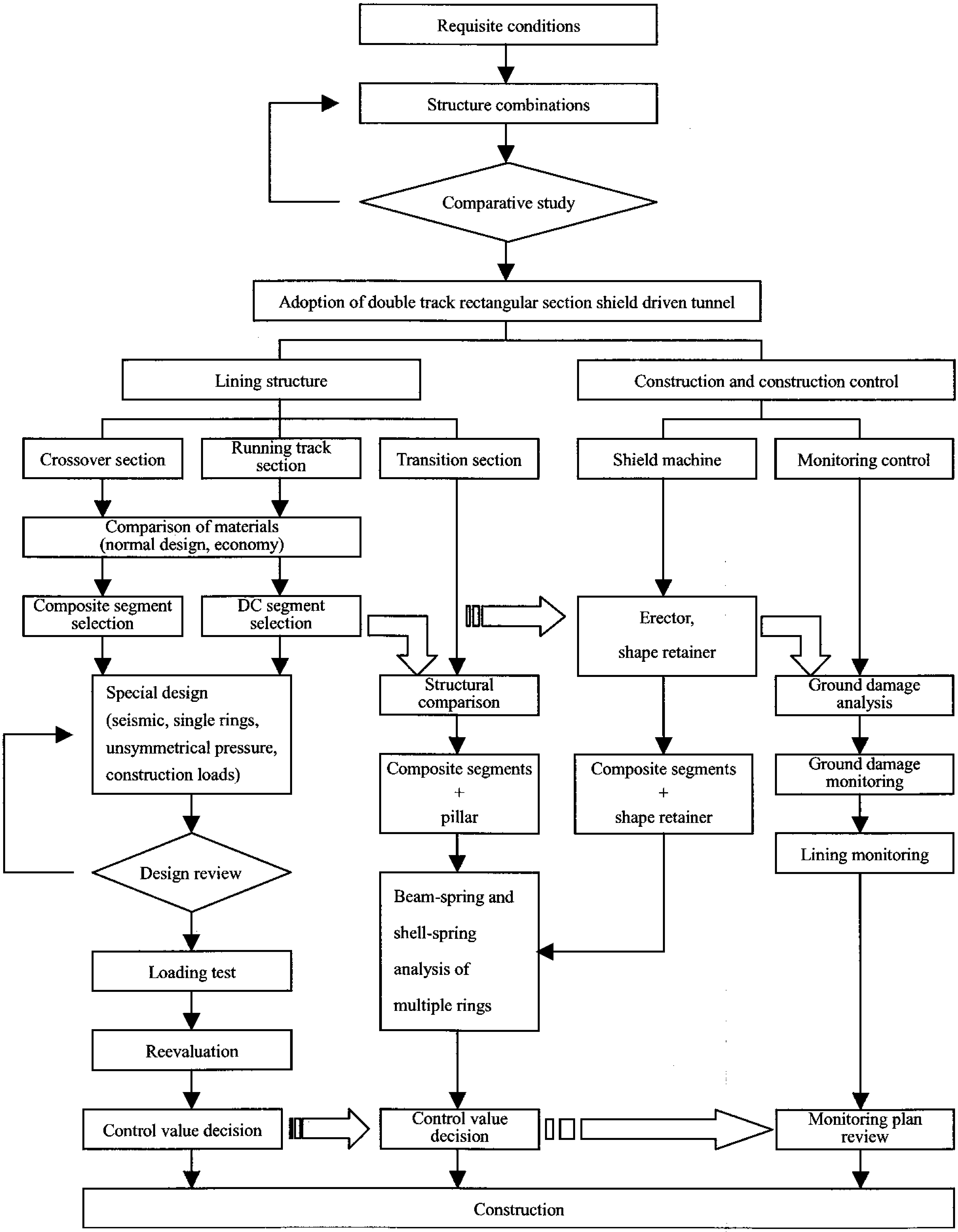


Figure 1. Flow of plan determination.

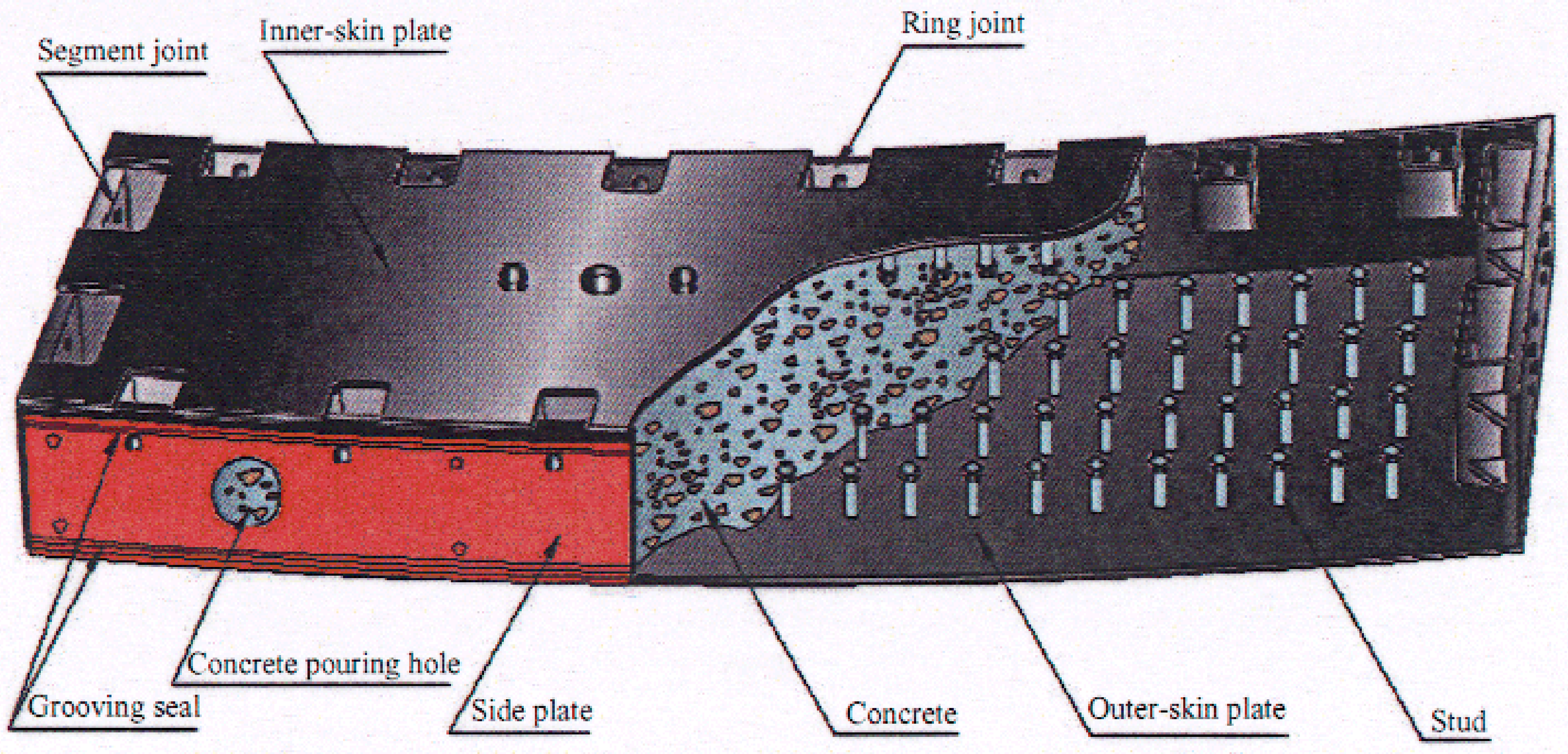


Figure 2. Sandwich type composite segment.

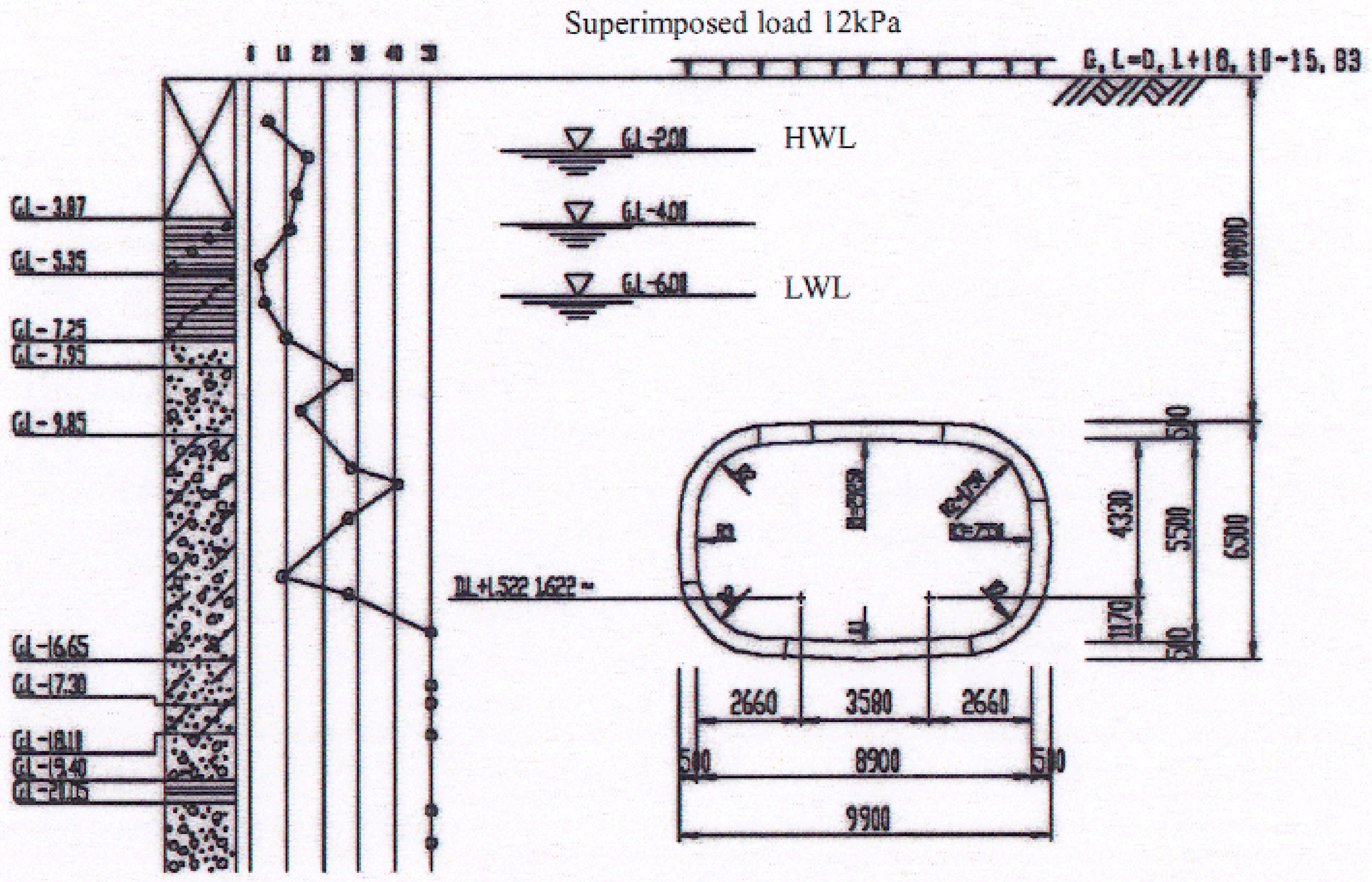


Figure 3. Design cross section of composite segments in crossover section.

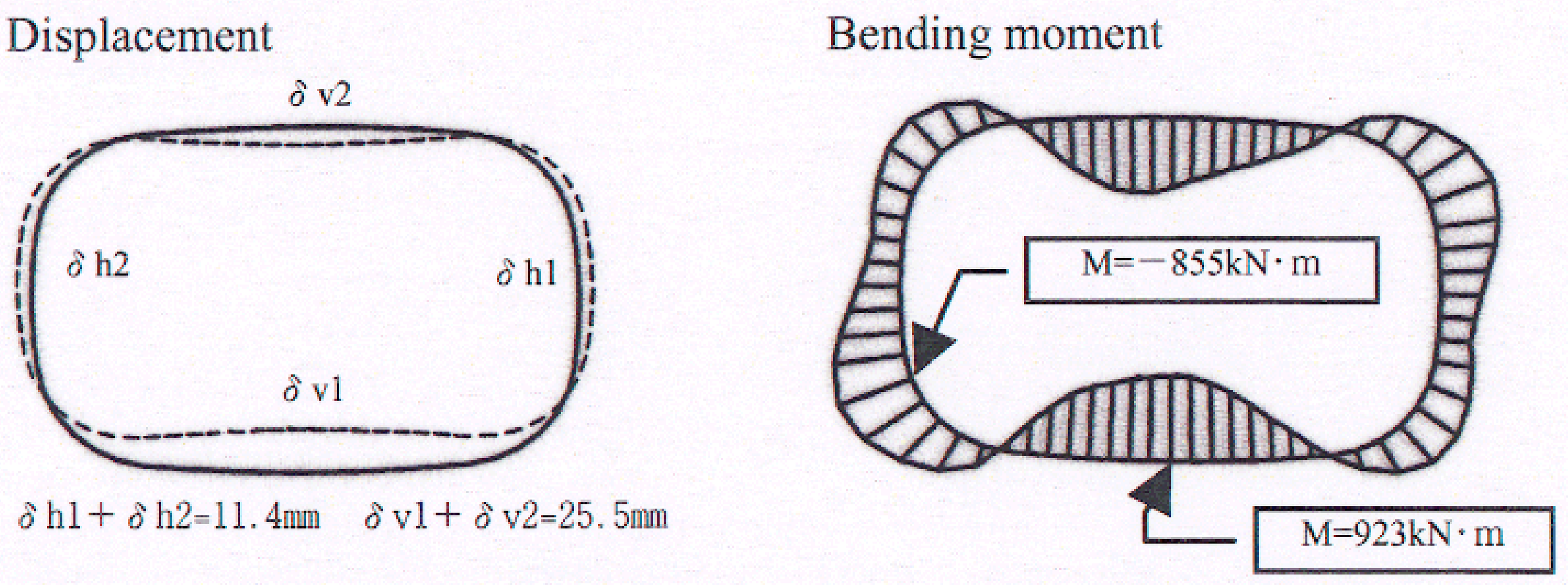


Figure 4. Stress resultants in composite segments in crossover section.

3.2 *Design method*

The design of the segmental lining was based on calculations by beam-spring model in which the joints were considered as springs and the segments themselves as beams. As loading conditions, consideration has been given to normal load (full earth pressure load, unsymmetrical earth pressure load), seismic load (earthquake motion level I, II), construction load (backfill grouting pressure), etc.

3.3 *Crossover section*

Sandwich type composite segments that have a 500mm girder depth will be used in the crossover section (single tier, single span). Secondary lining will not be provided except in the invert. These segments have stud shear connectors on both the inner and outer steel skin plates which produce the composite effect by acting together with the concrete placed inside. Joints are of a type in which joint plates are tightened by bolts. (Figure 2)

Table 2. Specification of composite segments (crossover section).

Height, width, length (mm)	6500 × 9900 × 1000
Girder depth (mm)	500
Ring division	7 segments
Material (steel)	SM490
Total weight / ring	375.2kN (38.26t)
Steel shell weight / ring	113.7kN (11.60t)
Concrete weight / ring	261.4kN (26.66t)
Segment weight (max.)	69.9kN (7.13t)
Joints between rings	M33 × 34 bolts / ring
Joints between segments	M36 × 8 bolts / joint

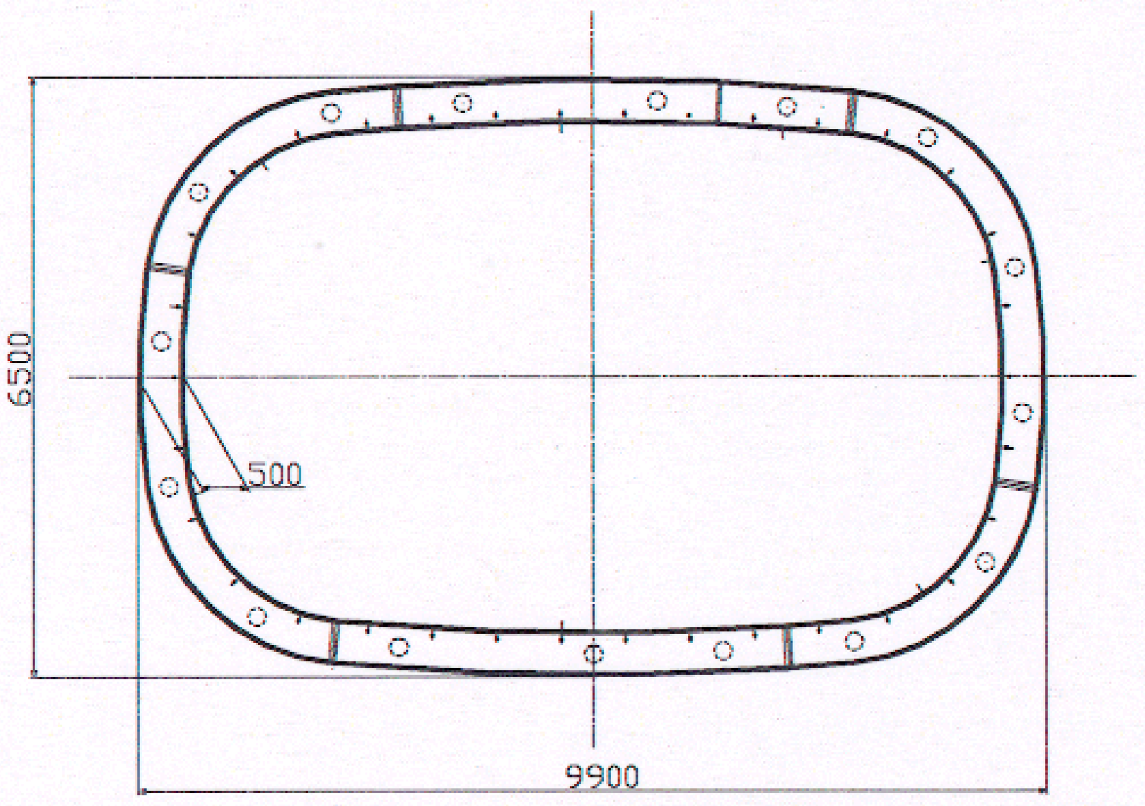


Figure 5. Overall structure of composite segments in crossover section.

The conditions of normal loading are shown in Figure 3, and the stress resultants in Figure 4. Also, the overall view of segment structure is shown in Figure 5 and the specification in Table 2.

3.4 *Running track section*

The running track section (single tier, double span with center pillar) is planned with ductile cast iron segments (DC segments) that have a 350mm girder depth. Because large moments develop at the heads and feet of the pillars, the segments at these points are designed as corrugated structures and the other segments are designed with four girders.

The conditions of normal loading are shown in Figure 6, and the stress resultants in Figure 7. Also, the overall view of segment structure is shown in Figure 8 and the specification in Table 3.

3.5 *Transition section*

Because the mode of deformation of the lining changes where the composite segments without a center pillar change to DC segments with a center pillar, a transition section is provided. The structure of the lining in the transition section consists of composite segments provided with a center pillar, and concentration of stress into this center pillar is prevented by gradually varying the length of the

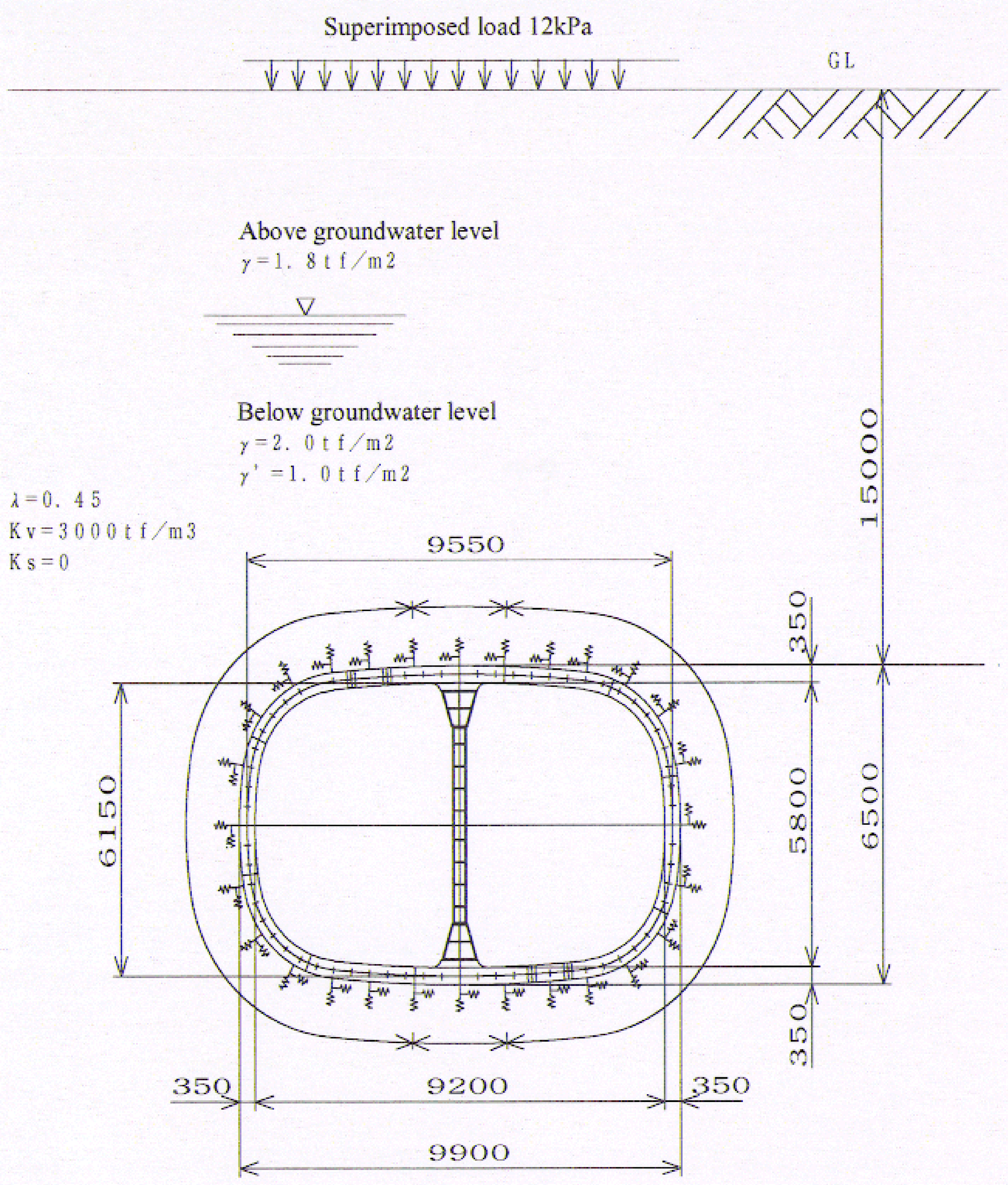


Figure 6. Design cross section of DC segments in running track section.

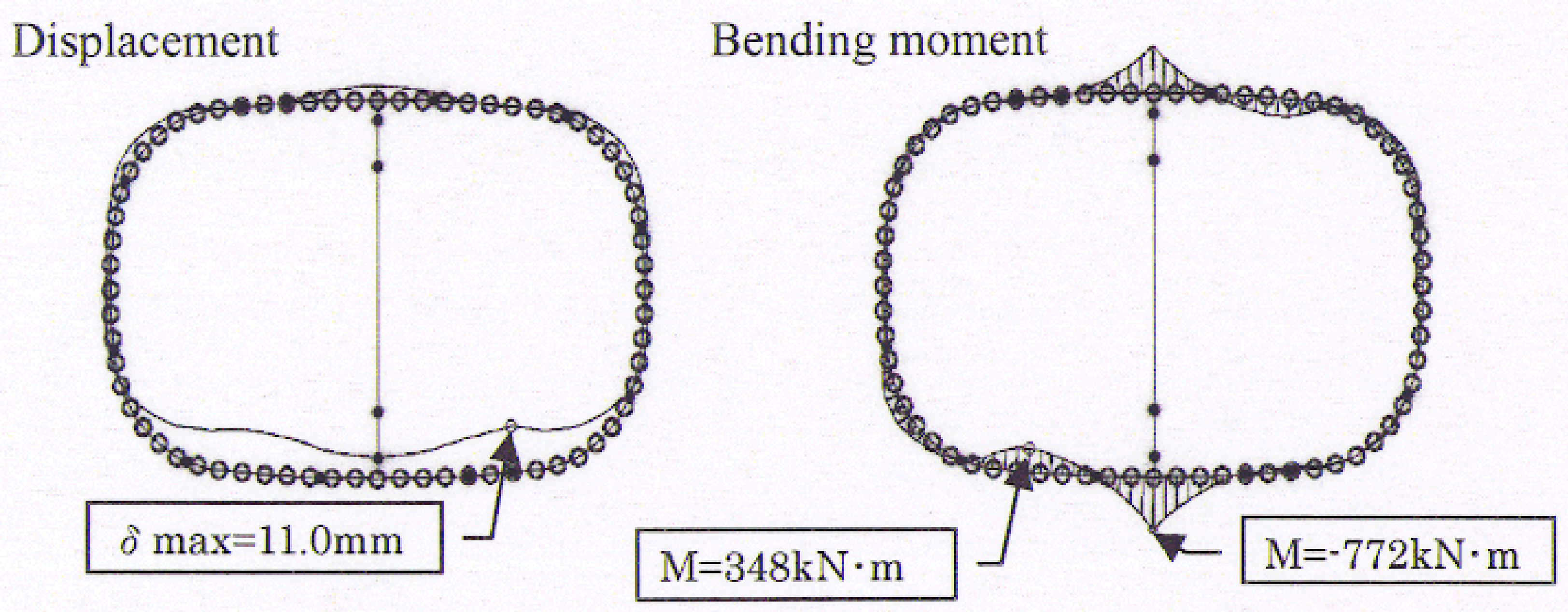


Figure 7. Stress resultants in DC segments in running track section.

Table 3. Specification of DC segments (running track section).

Height, width, length (mm)	6500 × 9900 × 1200
Girder depth (mm)	500
Ring division	12 segments + 3 (pillar, head, foot)
Material	Ductile cast iron
Total weight / ring	193.3kN (19.72t)
Iron shell weight / ring	170.9kN (17.44t)
Concrete weight / ring	22.4kN (2.28t)
Segment weight (max.)	27.8kN (2.84t)
Joints between rings	M30 × 68 bolts / ring
Joints between segments	M30 × 6 bolts / joint

center pillar. A view of the transition section is shown in Figure 9.

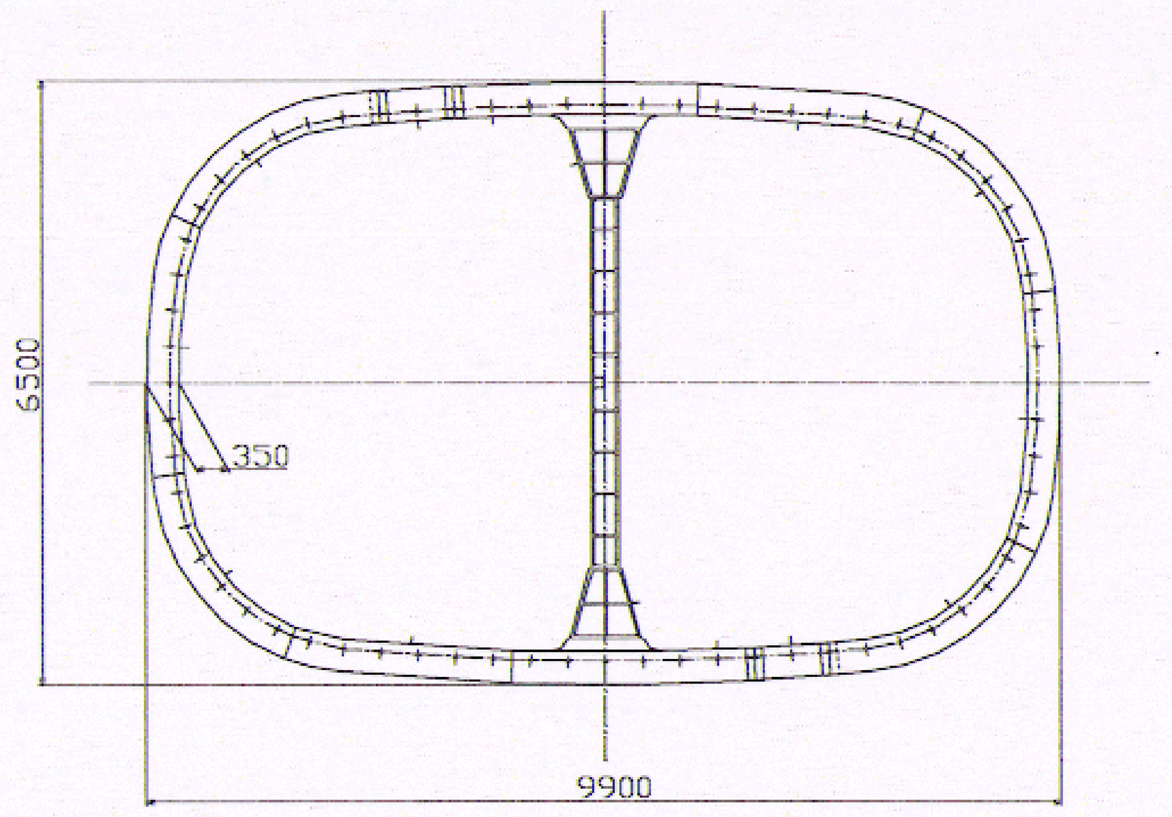


Figure 8. Overall structure of DC segments in running track section.

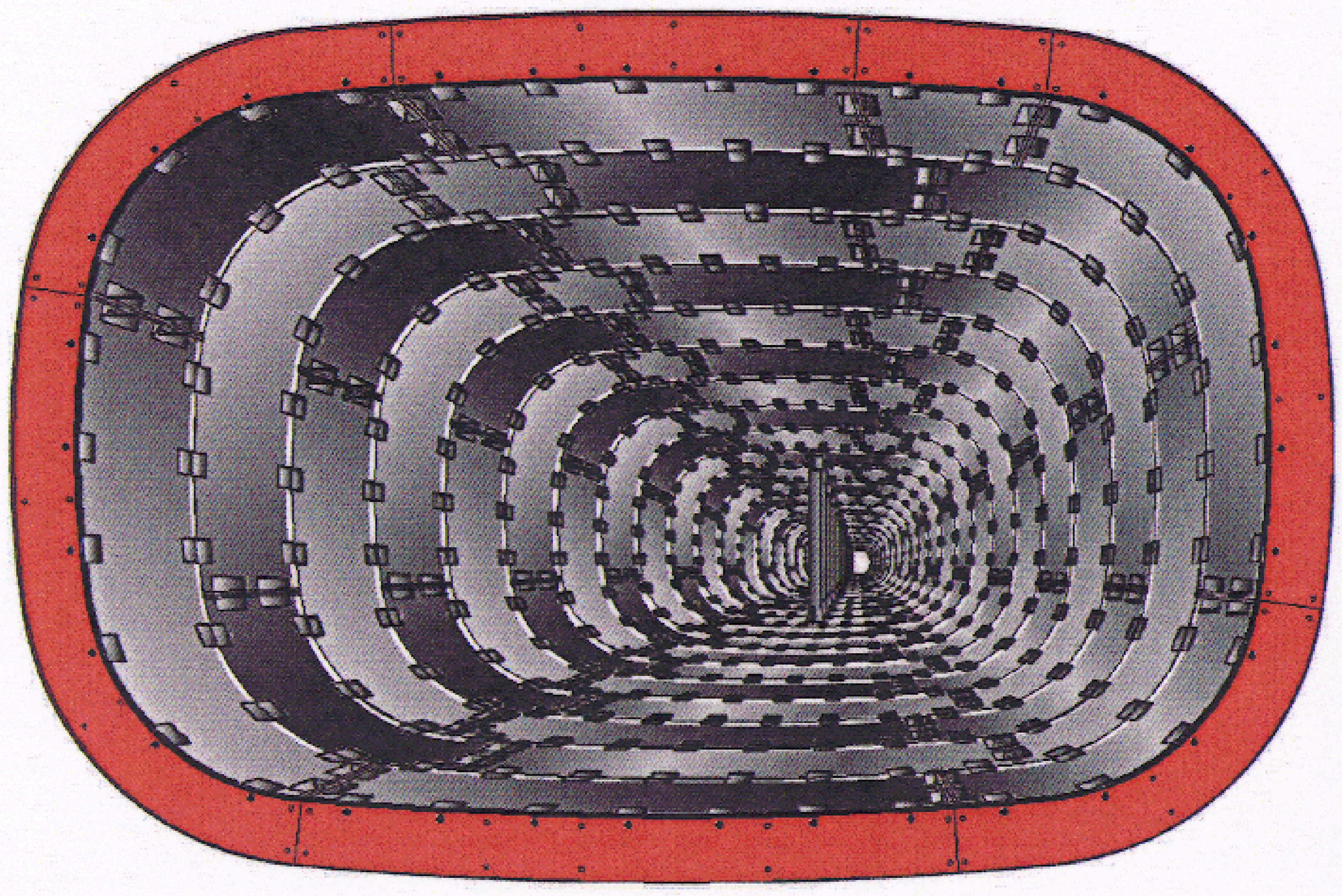


Figure 9. View of transition section.

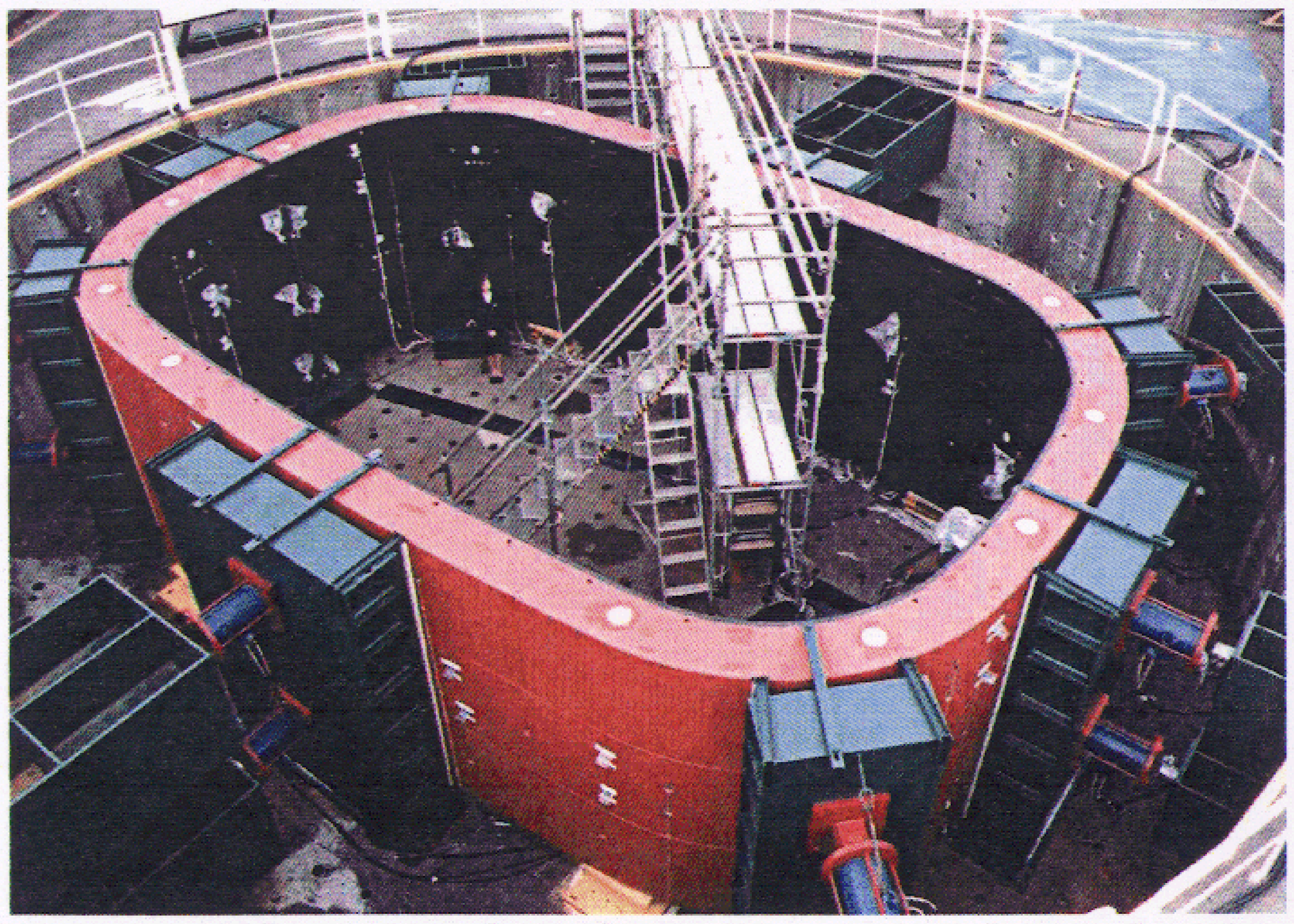


Figure 10. Loading test on composite segment rings.

4 SEGMENT LOADING TESTS

In the loading tests, the safety of the linings and the adequacy of the design method were evaluated by directly applying to single segments and full segment rings loads that were near to the design loads. Views of the loading test on each type of segment ring are shown in Figures 10-11.

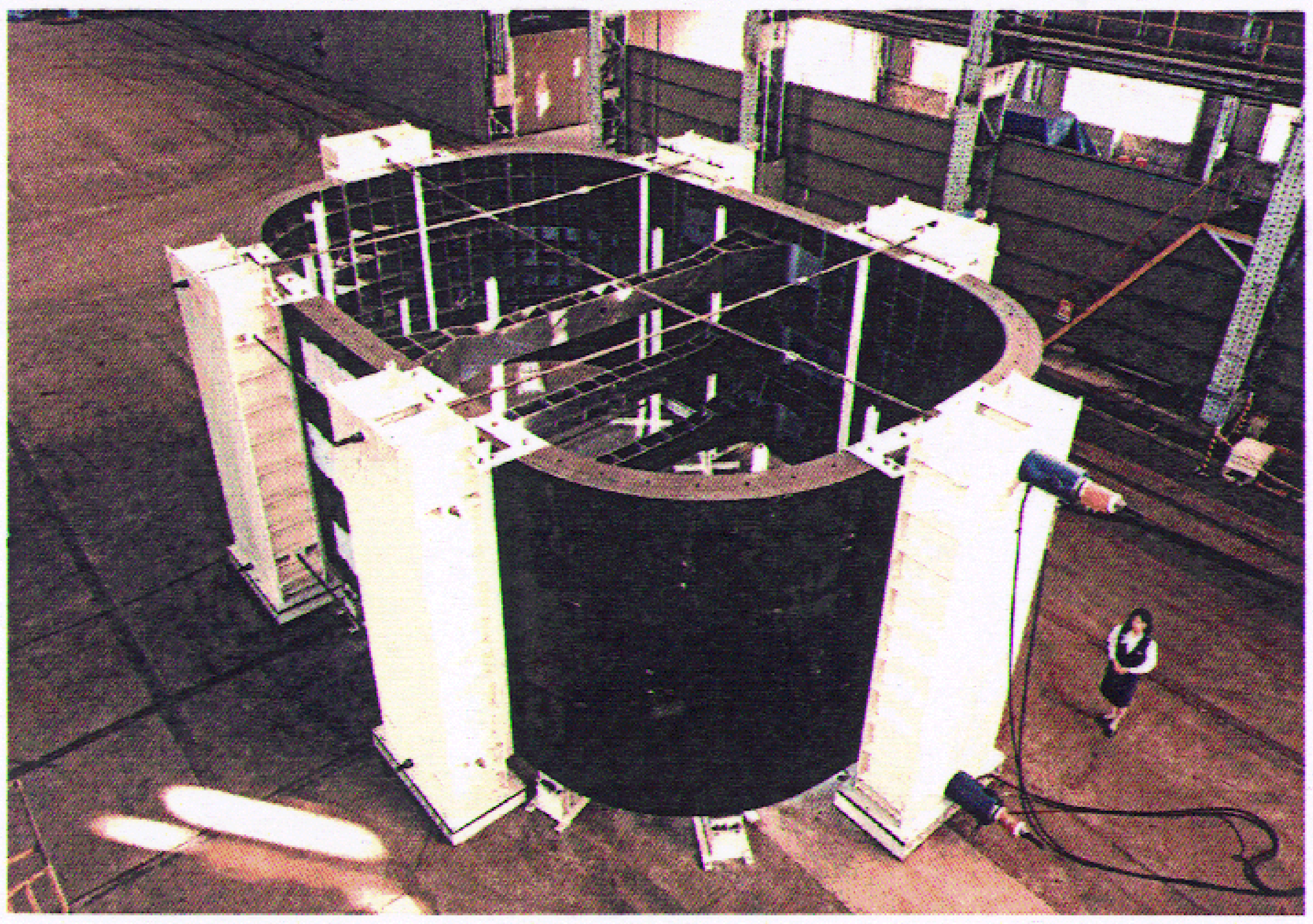
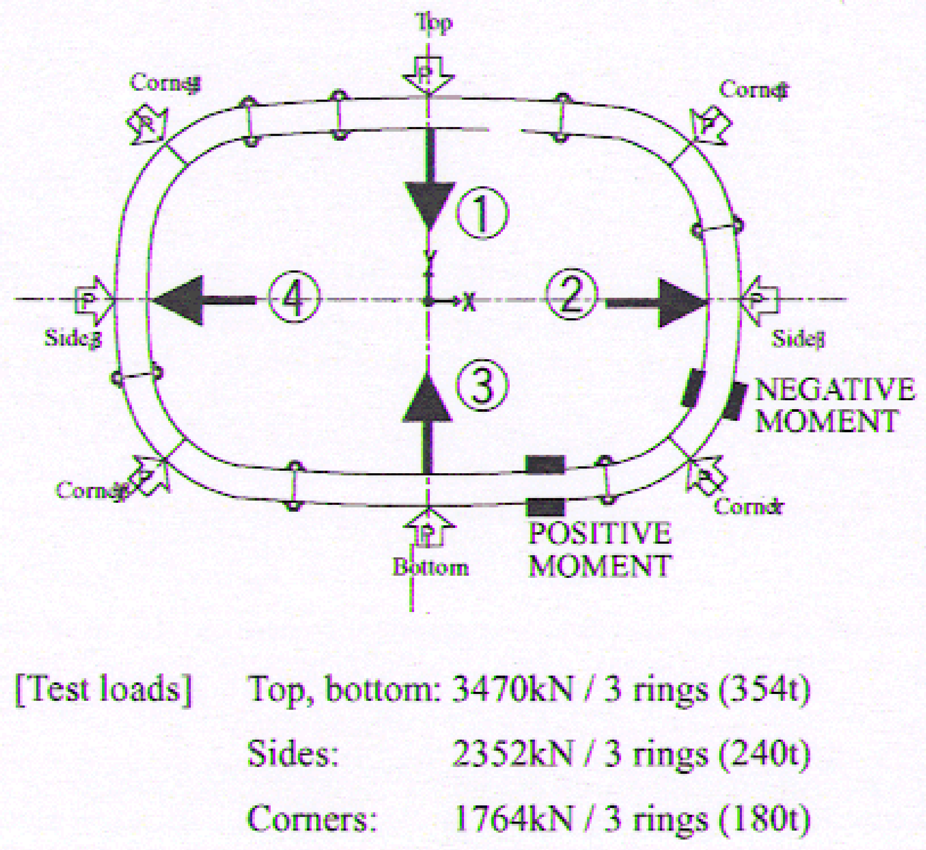


Figure 11. Loading test on DC segment rings.



Middle ring displacement (mm)

Position	Test	Analysis
①	15.1	16.4
②	6.5	6.6
③	15.7	14.4
④	6.4	6.7

Skin plate strain (μ)

		Test	Analysis
Positive moment	Inside	748	1024
	Outside	-625	-838
Negative moment	Inside	-630	-832
	Outside	661	833

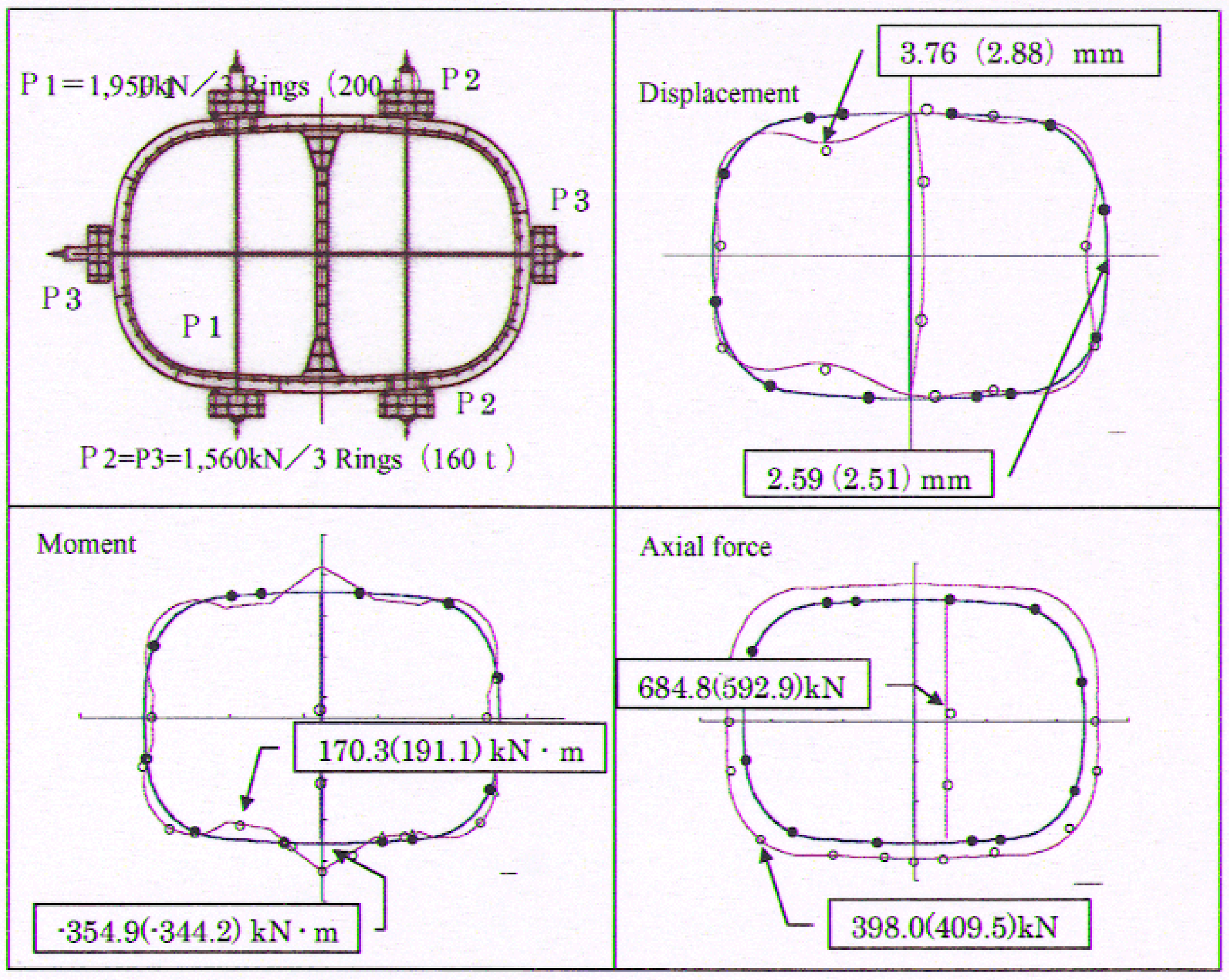
Figure 12. Results of loading tests on composite segments.

4.1 Composite segments

Loads nearly equivalent to the design loads were applied to the composite segment rings from eight directions. (Fig. 12) The amounts of lining displacement under this loading are shown in that figure along with the design values. The two generally conform with each other, thus confirming the adequacy of the design model. The amounts of skin plate strain also are less than the analytical values (approx. 76%), and both strain and displacement generally returned to their origins after the loading was removed. From this, it was judged that no extraordinary strain or deformation will develop.

4.2 DC segments

The distribution of bending moment, axial force and displacement which developed under loading are shown in Figure 13 in comparison with the results of analysis. The measured values and analytical values are generally close to each other, thus indicating that the beam-spring model satisfactorily simulates the behavior of the rectangular lining. Also, a comparison was made between analytical values and measured values at the joint plates of joints between



Note: Numbers are test values. Analytical values in ( ).

Figure 13. Results of loading tests on DC segments (unsymmetrical pressure load).

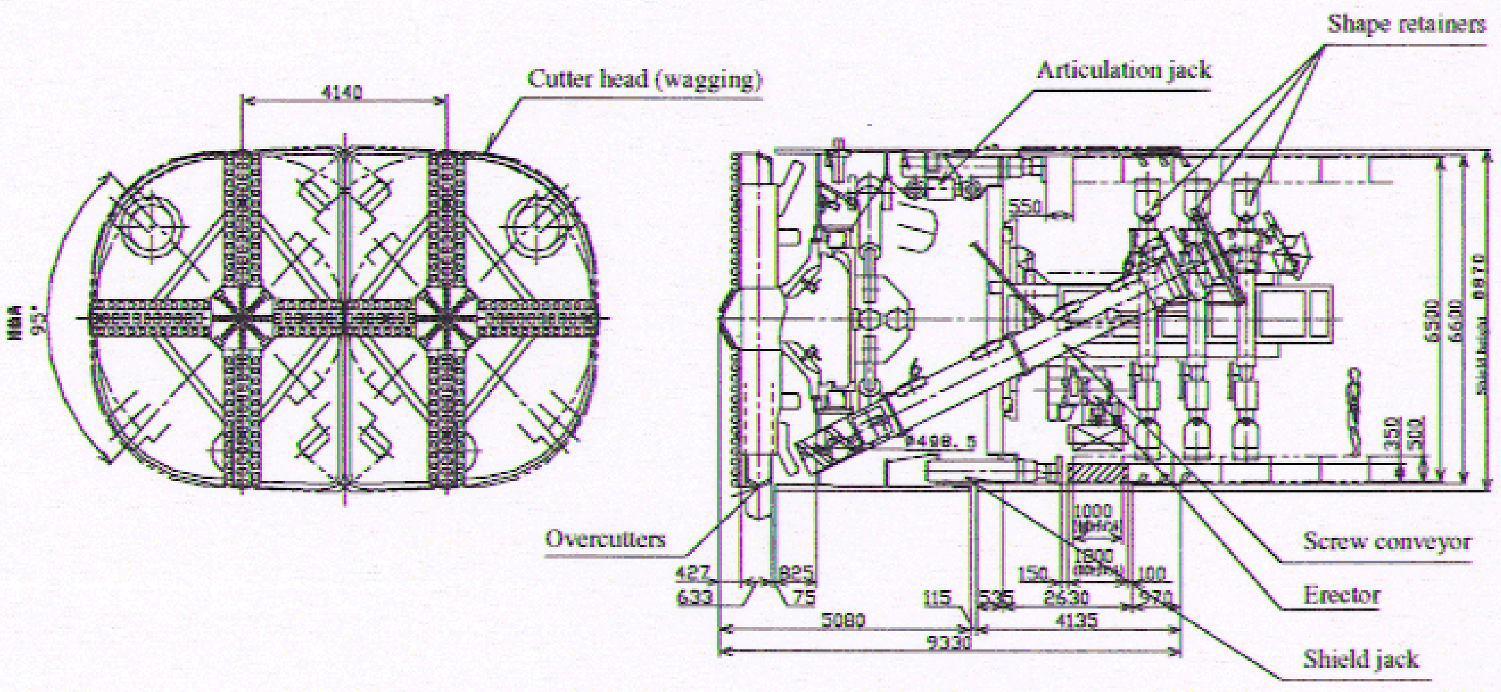


Figure 14. Overall view of Wagging Cutter Shield Machine.

segments, where the maximum stresses develop. The measured values were less than the analytical values (approx. 70%) and both strain and displacement generally returned to their origins after the loading was removed. From this, it was judged that no extraordinary strain or deformation will occur.

5 CONSTRUCTION PLAN

5.1 Rectangular cross section shield machine

Chiefly because of the site conditions (small surface land area, neighboring hospital) a shield machine of high density slurry type was adopted, and a "wagging cutter" was adopted as the excavating mechanism. This Wagging Cutter Shield excavates the tunnel face by means of a cutter head which performs an oscillating movement (wagging) within a fixed angle, and the corners of the cross section are cut by overcutters. An overall view of the machine is shown in Figure 14 and the specification in Table 4.

In order to handle large segments of differing shape, erectors which can be controlled on six axes were newly developed. Because the amount of deformation of composite segments is large, it is planned to equip the machine with shape retainers as shown in Figure 15.

Table 4. Specification of shield machine.

Total shield jack thrust	77,450kN
Thrust / unit area	$1229 kN/m^2$ (area: approx. $63m^2$)
Shield jack thrust	2941kN × 1400st × 8 jacks
	2451kN × 1400st × 16 jacks
	2451kN × 1700st × 6 jacks
Total articulation jack thrust	61,200kN
Articulation jack thrust	2550kN × 24 jacks
Cutter head wagging torque (high speed: 1.5 cycle/min) (α depends on average excavation radius)	max. 6301; min. 3822kN•m (α = 20.7; 15.0)
Cutter head wagging torque (medium speed: 1.25 cycle/min) (α depends on average excavation radius)	max. 8020; min. 4865kN•m (α = 26.4; 19.4)
Cutter head wagging torque (low speed: 1.0 cycle/min) (α depend on average excavation radius)	max. 10,025; min. 6082kN•m (α = 33.0; 23.9)
Wagging jack thrust	3432kN × 2 jacks
Assisting jack thrust	1961kN × 2 jacks
Cutter head wagging angle	95°
Screw conveyor torque	normal: 68kN•m, at 15.5MPa
	at max. torque: 101kN•m, at 23.0MPa
Screw conveyor speed	normal max.: 12.8 rpm
	at max. torque: 8.7 rpm
Screw conveyor discharge	normal max.: $165m^3/h$ each × 2
	at max. torque: $112m^3/h$ each × 2

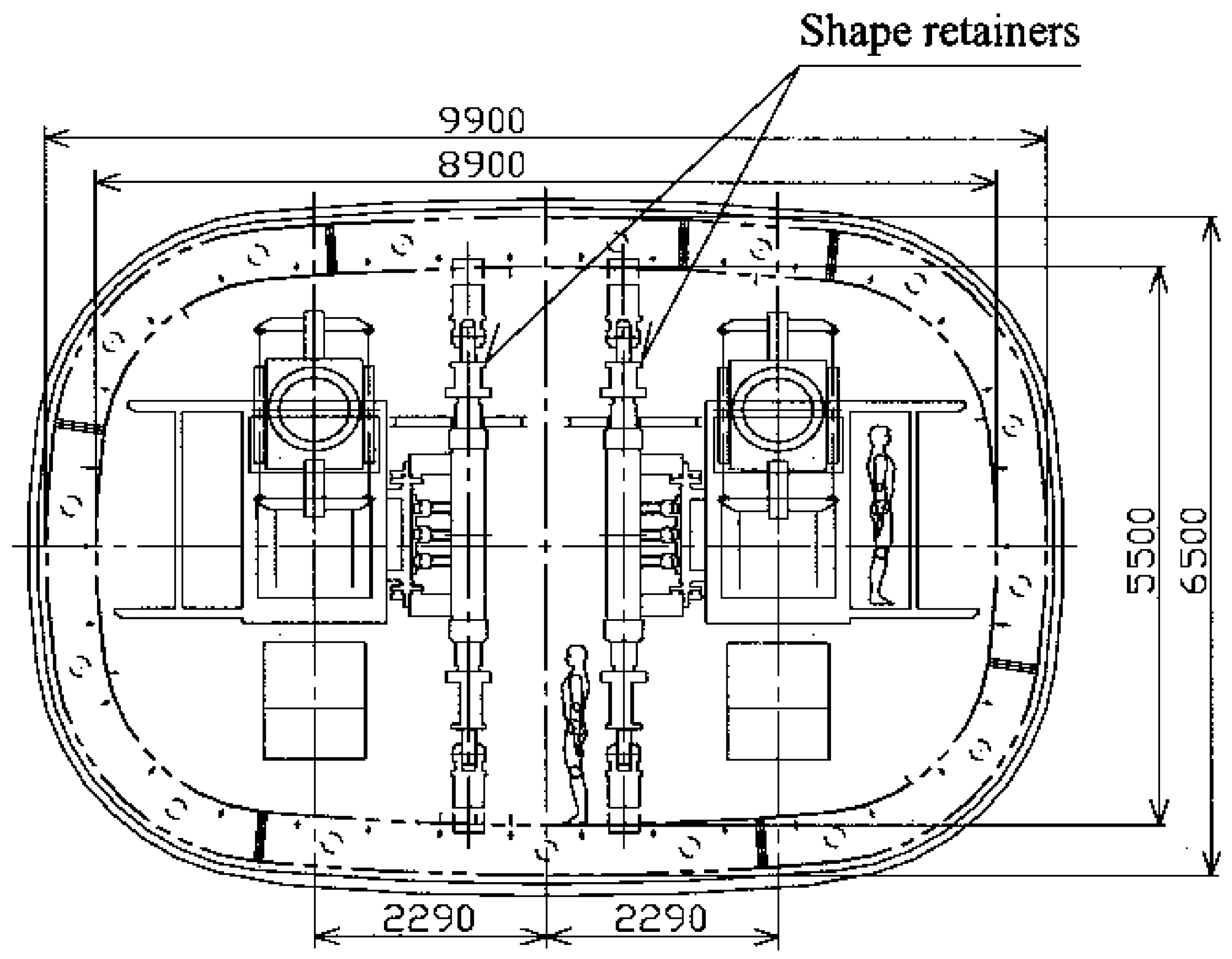


Figure 15. Segment shape retainers.

5.2 Monitoring control

Monitoring of various quantities is being planned in order to grasp the loads that act on the lining, the behavior of the lining, and the effect on the surrounding ground.

6 CONCLUSION

Construction was commended in October 1999. Assembly of the rectangular shape shield machine within the launching shaft will be commenced in the autumn of 2001, and launching is scheduled in the spring of 2002. This is a shield driven tunnel of unprecedented large, flattened cross section, and all of the persons involved are united together to achieve successful completion under the guidance of the Kyoto City Construction Technology Committee, the chairman of which is Professor Adachi of Kyoto University, and its Rectangular Shape Shield Working Group.