Development of a New Composite Segment for Large-Diameter Shield Tunnels

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ABSTRACT

The authors developed a new type of segment for the actual construction of shield tunnels. This newly developed segment for tunnel lining is composite structure type combining box-shaped ductile cast iron shell frame and reinforced concrete. Thanks to the higher strength and the higher rigidity of this DRC Segment comparing to the conventional RC Segment, the great reduction of the segment thickness can be achieved, which enables the excavating cross section area smaller by 7-10%. Jointing structure of the segment is not bolt-jointing, but wedge application type, which can make the time of erecting the segments shorter only by pushing in the segments to the axial direction of tunnel with the shield jack. In addition, because of no bolt box, the inside surface is completely smooth and flat and no secondary lining is required. Thus DRC segment is suitable for water channel tunnel which is subject to internal water pressure and for highway and railway tunnel of large diameter. DRC segments were adopted as two tunneling projects, the one was discharge channel tunnel, and the another was highway tunnel.

1. INTRODUCTION

In tunnel construction using the shield tunneling method, (i) the time required for erecting segmental linings has a great impact on the construction time, (ii) the cost of segment accounts for a large percentage of construction cost and (iii) the amount of excavated material dependent upon the thickness of the segmental lining also has an impact on the construction cost. The contractors engaged in shield tunneling these days have therefore been demanding a high-strength segmental lining structure and a joint structure that enables rational construction to minimize the cost of lining members and streamline the construction process. Tunnels subject to internal water pressure such as floodway tunnels require the structures of the tunnel body and joint that can resist high tensile force and the smooth inner surface to reduce head loss at the time of flood water conveyance. The authors developed a new type of segment that meets the above needs and applied it during the actual construction of shield tunnels.

The new type of segment is a composite type combining a box-shaped ductile cast iron frame with reinforced concrete. It is referred to as "ductile reinforced concrete (DRC) segment". It is stronger and more rigid than conventional reinforced concrete segments, so it can constitutes a lining much thinner, which results in 7 to 10% smaller tunnel cross section.

Wedge-type connectors rather than bolts were used for coupling DRC segments. The segments are coupled from inside the tunnel without using any bolts or other connecting members. The segment
therefore suffers no loss of area to reserve the space for bolt boxes that would be required for connection by bolts. Thus, the segment structurally experiences no strength reduction due to the deduction in cross sectional area near the joint. Concrete is placed in segments in a factory, so the inner surface of a segmental lining is completely smooth and a tunnel with a smooth inner surface can be constructed without applying any secondary linings. With the use of longitudinal wedge-type connectors, segmental linings can be erected rapidly by simply thrusting segmental linings by a shield jack advancing in the direction of tunnel axis. Thus, rational and rapid construction is realized.

DRC segments with the above benefits are applicable to water conveyance tunnels subject to internal water pressure or large-diameter highway and railway tunnels.

DRC segments were employed on two projects, a tunnel accommodating an underground river and a highway tunnel. The underground river tunnel has an outer diameter of 11.8 m and a length of 1235 m. The erection of segmental linings was completed on May 29, 2002. The time required for erecting segmental linings was approximately half that for conventional coupling with bolts. The internal structure of the tunnel was nearly circular and no leakage of water occurred in the tunnel. The highway tunnel of an outer diameter of 12.83 m is scheduled to be constructed in 2003.

This paper describes the benefits of the new type of segment, structural tests conducted during the segment development and the design and construction conditions on the above projects.

2. BENEFITS AND OUTLINE OF DRC SEGMENT

2.1 Structure of the segments

Figure 1 shows the structure of a DRC segment. The DRC segment is of a composite structure consisting of ductile cast iron, reinforcement and concrete. A box-shaped ductile cast iron frame with built-in reinforcing ribs is equipped with reinforcing bars and filled with concrete. The structural benefits of the DRC segment are described below:

1) The composite segment guarantees high strength and rigidity, so it can constitute a segmental lining of smaller thickness.
2) Placement of concrete lining on the side of the inner surface of the tunnel makes smooth inner surface of the segmental lining.
3) Durability and anti-corrosiveness have been increased by filling the ductile cast iron frame with concrete.
4) The segment is covered with ductile cast iron on its five sides except the one facing the inner surface of the tunnel. The segmental lining therefore suffers no cracking through itself, unlike concrete segmental linings, and no falling of segments during the erection or handling of segmental linings. Thus, high level of waterproofing can be ensured.
5) For coupling segments and segmental linings, AS joints and anchor joints built in the segment are used, respectively. This prevents the loss of cross sectional area to provide space for joint boxes.

Figure 2 presents a schematic of segmental lining erection. Segmental linings are connected to each other by simply thrusting rings by a shield jack in the direction of tunnel axis. Thus, effective and rapid construction is realized.

2.2 Structure of the circumferential joint

Segments are connected to each other using AS joints (Figure 3). The joints are inserted longitudinally as if like wedges. While the segments are connected to each other, members subject to buckling
distortion called backup members, which are placed behind the AS metal coupler, apply reaction while they are deformed. Thus, desired connecting force can be applied to the joint.

2.3 Structure of the longitudinal joint

Anchor joints are employed for connecting segmental linings (Figure 4). This type of anchor adopts the principle of a mechanical anchor. Segmental linings are connected to each other as the sleeve, a feather-like deforming member, fits between the wedge, a conical member, and the housing, a cylindrical member while adjusting the position. The collar, a member subject to buckling deformation, which is attached behind the wedge checks excessive thrust.

3. DESIGN AND PERFORMANCE TEST OF DRC SEGMENT

Before applying DRC segments, performance evaluation tests were carried out using full-scale specimens to identify the basic structural properties in such terms as the stiffness of the segment and stiffness at the joint represented by a spring and to measure the ultimate strength. The method for designing the segment was established based on the evaluation of the performance test results. A flowchart of the design and development process is shown in Figure 5.

This paper presents the results of verification of the composite structure, one of the features of the DRC segment. The segment has a high flexural stiffness and ultimate strength owing to the structure combining ductile cast iron and reinforced concrete. A unit test was conducted for the segment by applying simple bending loads using full-scale plate specimens. Then, the load-central displacement relationship and the strain distribution in the cross section obtained by the test were compared with the results of nonlinear finite element analysis. As a result, it was verified that the segment has the characteristics of a composite structure. Figure 6 compares the relationships between the load and central displacement obtained by the test and the finite element analysis. Figure 7 presents a model used for the nonlinear finite element analysis. Figure 8 gives a comparison between the test and calculated values for the strain distribution in the cross section.

As a result of the above studies, it was verified that the DRC segment has the flexural stiffness and strength as a composite structure.
**Fig. 5 Flowchart of design and development process**

1. Start
2. Determine torsional stiffness at circumferential joint
3. Determine shear stiffness at longitudinal joint
4. Determine flexural and axial stiffness of segment
5. Calculate cross sectional force
6. Design circumferential joint
7. Design longitudinal joint
8. Design the segment
9. Check under permanent load
   - Segment bending test
   - Unit tensile test for joint
   - Unit connection test
   - Bending test for joint circumferential (apply axial force)
   - Contact bending test
10. Check loading during construction
    - For thrust of the jack
    - For load to be carried

**Goal**

**Fig. 6 Unit bending test - Relationship between load and central displacement (Positive bending)**

- Applied load (N)
- Center displacement (mm)
- Test result
- Analyzed value for structure
- Analyzed value for ductile segment only

**Fig. 7 Nonlinear finite element analysis model**

- a) Ductile cast iron
- b) Reinforcing bar
- c) Concrete
4. EXAMPLES OF CONSTRUCTION OF DRC SEGMENTAL LININGS

DRC segments were employed on two projects. One is an underground river tunnel and the other is a highway tunnel. The former tunnel has an outer diameter of 11.8 m and a length of 1235 m. The erection of segmental linings was completed on May 29, 2002. The highway tunnel with an outer diameter of 12.83 m is scheduled to be constructed in 2003 over a length of 132 m.

In all work sections on the former project, construction was completed without any trouble. No leakage occurred in the tunnel. The construction on the former project is described below.

4.1 Time required for segmental lining erection

Actual time required for automatic segmental lining erection is shown in Figure 9. The tunnel has a large diameter of 11.8 m, but a segmental lining was erected in 33 minutes at the shortest, thus rapid construction was possible. The time was approximately half that required for lining erection using conventional bolting.

4.2 Circularity during segmental lining erection

The distance to the inner surface of the segmental lining was measured around the internal perimeter of the erected ring by the laser sensor attached to the erector arm of the shield tunneling machine. The measurement was used to calculate the radius of the inner circle. Then, the circularity of the tunnel ring was verified from the variance between the design and calculated radiiuses. Figure 10 shows the results of measurement of circularity. The variance was approximately 8 mm. Thus, the erection of the segmental lining proved satisfactory.
4.3 Bond strength at the joint

In order to confirm that the bond strength in the designated range was left at the joint at the completion of construction, the strain at the joint was measured. Figure 11 shows the distribution of strain immediately after the erection of the lining. Figure 12 shows the strain distribution right after the shield tail passed the erected lining. The strain was within the range of the design level at all the joints. The availability of sufficient bond strength was thus confirmed. It was also verified that the bond strength remained almost unchanged immediately after the ring was erected and after the segmental ring was left in the ground following the passing of the shield tail.

5. CONCLUSIONS

The authors developed the DRC (ductile reinforced concrete) segment that provides for the reduction of the thickness of lining members and automatic connection of segments and segmental rings to reduce the cost of lining members and streamline segmental lining erection, and applied the segment on actual projects. The following results were obtained by the test for developing the segment and the construction of segmental linings.

5.1 Reduction of the cost of lining member

It was verified from the result of the test for developing the segment that the segment worked as a composite structure. The results of the nonlinear finite element analysis that was made before construction, or calculated values, were in good agreement with the test values. Thus, the method for assessing the stiffness of the body of the segment was found to be appropriate.
Judging from the knowledge obtained, applying the DRC segment is expected to enable the reduction of thickness of segmental linings, effective design of segment body and the reduction of the diameter of excavation and of the excavated material. Thus, the total construction cost can be minimized.

5.2 Streamlining of segmental lining construction

Actual construction using DRC segments resulted in the reduction of segmental lining erection time to approximately half that for segmental linings employing conventional bolting of rings, nearly circular inner tunnel ring and no leakage throughout the lined distance. Thus, DRC segments were found to enable rapid and rational construction.