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Development of Composite Concrete-Packed Steel Segment

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Abstract

To equip underground spaces with infrastructures such as underground rivers and transportation systems for the purpose of reviving urban areas, it is expected that these spaces will be constructed deeper underground and larger in size. Therefore, the segments that cover the surfaces of such structures need to have high performance in terms of bending-resistance and water-resistance. The authors developed a new composite concrete packed steel segment, Composite CP segment, which can resist large earth and water pressure, by uniting steel with high tension resistance and water-tightness and concrete with high compression resistance. This paper describes the characteristics of two different Composite CP segments applied for different load conditions, provides an evaluation of the structural performance and the design method of Composite CP segments based on the test results, and reports about a construction site where Composite CP segments are being used.

1. Introduction

In the field of shield tunnel construction in recent years, it has become common practice to omit the secondary lining in order to rationalize the construction work from the standpoint of cutting costs and shortening the construction period. On the other hand, various new types of tunnels have been constructed–tunnels which are subject to exceptionally high internal water pressure (underground water channels, and rainwater reservoirs, etc. built as measures to prevent floods in urban areas), non-circular tunnels which are subject to extremely large bending moments (subway stations, etc.), and tunnels which are required to have very high earthquake resistance (those which are constructed near an active fault). The segments used for those tunnels are required to have higher performance than ever before.

In order to meet the above need, the structural materials division of Nippon Steel developed in 1990 a Concrete-Packed Steel Segment (CP segment) to take advantage of steel's superiority in tensile strength, elongation and water-tightness over concrete. The CP segment consists of a set of five segment pieces covered with a steel sheet on the outside. Concrete is placed in the steel shell at the factory. This segment has been used in many shield tunnels without a secondary lining. The CP segment is designed in the same way as the ordinary steel segment, that is, as a steel structure to support external load.

Today, in large cities, the ground under our roads is congested with subways, utility lines, telecommunication cables, water supply and sewerage systems, etc. to a considerable depth. In the future, therefore, underground facilities will have to be constructed even deeper. On the other hand, since the "Special Measures Law concerning Public Use of Deep Underground" came into effect in 2001, public awareness of urban renewal utilizing our subterranean resources has been growing. Under those conditions, it is likely that deep underground development in metropolitan areas will surge for-

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ward in the future. The linings of tunnels constructed deep underground are subject to massive earth and water pressures, which cause the compressive force acting upon the segment circumference to increase. Therefore, when the segment is designed as a steel structure, the cross-sectional area of the main steel girder necessarily increases. This makes the steel structure less economical than its concrete counterpart. In view of this situation, we have pressed ahead with development of a composite CP segment that allows for rational design of a tunnel to be constructed deep underground by taking advantage of the compressive strength of concrete. This paper describes the contents of the technological developments for two types of composite CP segment.

2. Outline of CP Segment

2.1 Characteristics of CP segment

The salient characteristics of the CP segment (see **Fig. 1**) are: (1) thanks to the outstanding strength of steel, the CP segment permits using a thinner lining than does the RC segment even when the bending moment acting upon it is very large, (2) since the secondary lining is unnecessary, it is possible to shorten the construction period, (3) since the CP segment is covered with steel plate, there is no risk that the concrete within may crack or break during construction, and (4) the CP segment has excellent water-tightness made possible by the application of waterproof welding and high-performance sealants.

2.2 Types and position of CP segment

As shown in **Fig. 2**, the CP segment is available in three types, each of which has its own structural characteristics.

The CP segment with four main girders, which takes advantage of the excellent tensile strength of steel, is capable of rationally resisting the tensile axial force that occurs in the tunnel circumferential direction. This type is suitable for tunnels which are subject to high internal water pressures.

The heavy-duty composite CP segment has main reinforcing bars piercing the longitudinal ribs to unite the packed concrete and steel shell and to permit arranging a lot of reinforcement. Since this type is capable of rationally resisting extremely large bending moments, it is suitable for use in deep, soft underground and for non-circular tunnels.

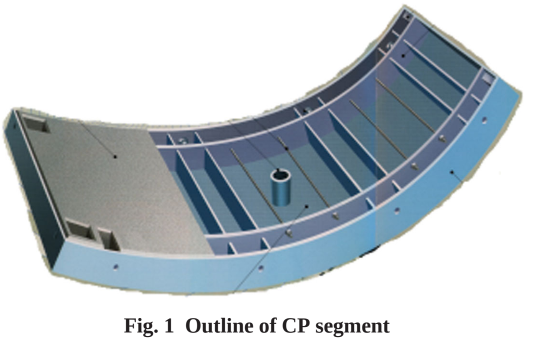
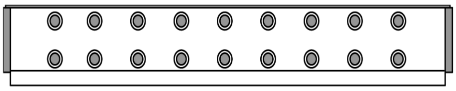
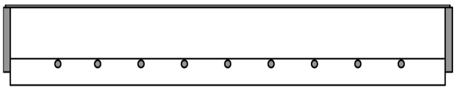


Fig. 1 Outline of CP segment

(a) CP segment with 4 main girders



(b) Composite CP segment for heavy loading



(c) Composite CP segment for light loading

Fig. 2 Cross section of CP segment (three types)

The light-duty composite CP segment has longitudinal ribs arranged so as to unite the packed concrete and steel shell. Having a simple structure, this type is capable of rationally resisting relatively large bending moments and hence is economical. It is suitable for tunnels for which neither of the above two types is very suitable.

Table 1 shows the design method for each type of CP segment and the conditions of the tunnels to which it is applied.

3. Development of Composite CP Segment (Heavy-duty Type)

3.1 Characteristics of segment structure

The heavy-duty composite CP segment (see **Fig. 3**) is designed for tunnels which are subject to both extremely large axial forces and bending moments. This segment has the following characteris-

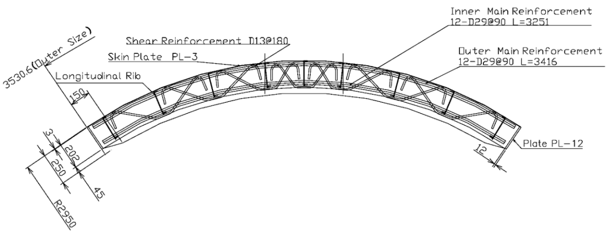


Fig. 3 CP segment for heavy loading

Table 1 Characteristics of each CP

Type	Design method	Suitable tunnel condition		
		Depth	Ground classification	Inner water pressure
CP segment with 4 main girders	Steel structure	–	Soft	Large
Composite CP segment for heavy loading	Composite structure	Deep	Soft	–
Composite CP segment for light loading	Composite structure	Deep	Hard	Middle
		Shallow	Soft	Small

tics.

(1) Reinforcement and concrete are arranged in a steel shell, and reinforcing bars are inserted through openings in the longitudinal ribs to secure the reinforced concrete to the steel shell.

(2) Oblique tension bars, each bent in the form of an M, impart high shear strength to the segment.

3.2 Structural characteristics of the segment proper and design method

In order to examine the structural characteristics of the composite CP segment and establish a design method for the segment, we conducted bending and jack thrust tests.

3.2.1 Bending test

(1) Purpose

The purpose of the test was to determine whether the steel shell and packed concrete would combine to resist the prescribed bending load.

(2) Outline of test

The test scheme is shown in **Fig. 4**. A uniform bending test with a loading point interval of 600 mm was carried out. The test piece used was a vessel-shaped unit with the concrete inner surface facing down. For the purpose of comparison, an RC segment test piece having the same ultimate yield strength as the above test piece was also used. In the test, the crack load, allowable load and yield load were applied once in that order. Then, each load was removed and reapplied. This procedure was repeated. Finally, the maximum load of the test apparatus was applied.

(3) Test results

Fig. 5 shows the relationship between load and vertical displacement at the center of each test piece. The RC segment showed a sharp decline in yield strength as the concrete collapsed after the ultimate yield strength was reached. By contrast, the composite CP segment displayed high deformation performance even after the ultimate yield strength was reached. **Fig. 6** shows the axial strain distributions in the steel in the direction of the girder height. It can be seen that the surface was maintained and the steel shell and packed concrete were behaving as a single unit. From this fact, it is considered possible to design the composite CP segment as a composite structure.

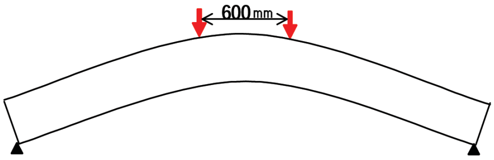


Fig. 4 Outline of bending test

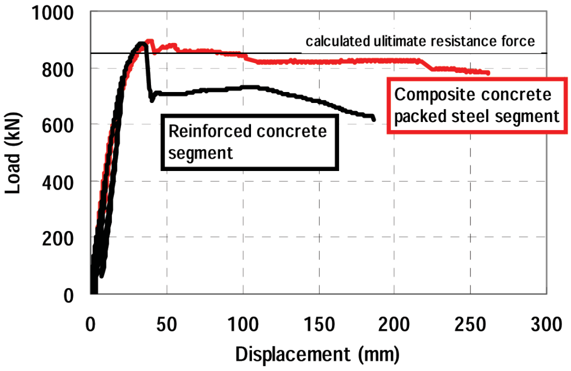


Fig. 5 Displacement-load relationship

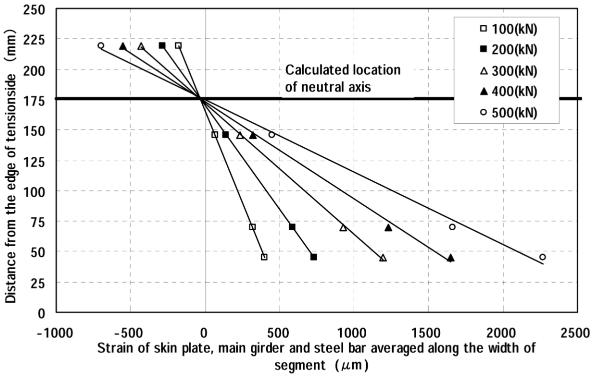


Fig. 6 Strain distribution along the height of segment

3.2.2 Jack thrust test

(1) Purpose

The purpose of the test was to study the jack thrust resistance mechanism of the composite CP segment—an exceptionally thin segment.

(2) Outline of test

The test scheme is shown in **Fig. 7**. Spreaders of the same size were fitted to the main girders on the upper and lower sides to restrain the widening of the effective area of resistance inside the segment so as to measure the segment resistance to the thrust of a single jack. With the center of gravity of the jack thrust placed at a point 10 mm inward from the segment centroid, the segment was subjected to the jack thrust test. After the allowable load was reached, the load was removed once. Then, the appearances of the concrete and skin plate surfaces were inspected. After that, the test was continued till the segment broke.

(3) Test results

The jack thrust load was increased up to approximately 10,000 kN, far exceeding the allowable load (4,126 kN) at which it was assumed that the concrete alone supported the jack thrust. However, the segment did not break. In particular, up until the allowable load was reached, neither cracks in the concrete surface nor buckling of the skin plate was observed. **Fig. 8** shows the distribution of jack

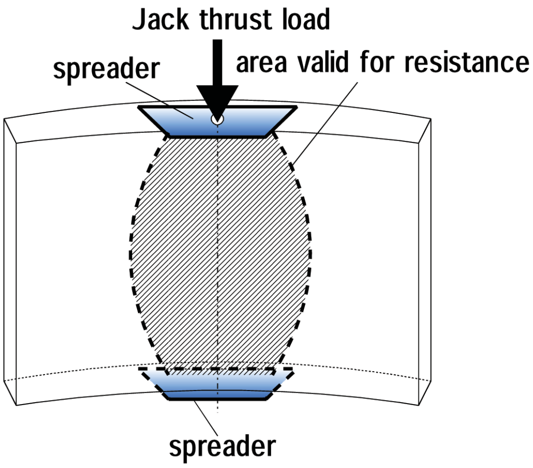


Fig. 7 Outline of jack thrust test

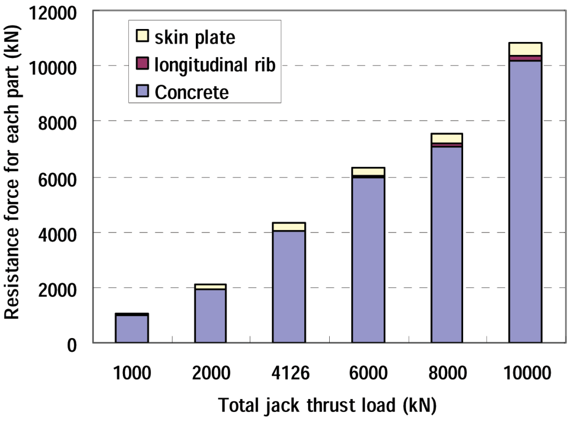


Fig. 8 Resistance force for each part against total jack thrust load

Photo 1 Bending test for joint

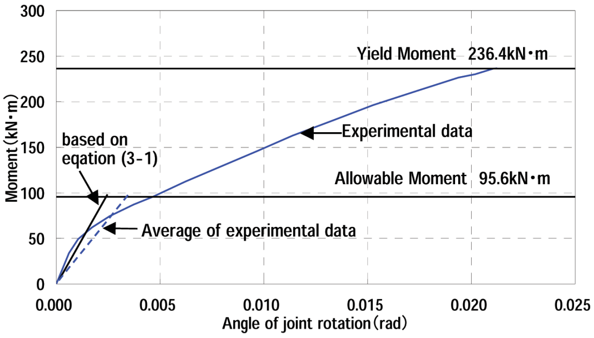


Fig. 9 Relationship between moment and angle of joint rotation

thrust load among the segment members. It can be seen that the concrete supports more than 90% of the load. Thus, it is considered that the segment can be designed safely on the assumption that the jack thrust load is supported by the concrete alone.

3.3 Segment joint structural characteristics and design method

The composite CP segment joint is of bolt-clamped construction via reinforcing joint hardware. In order to measure the rotary spring constant as an indicator of the segment joint flexural rigidity and the load-bearing capacity of the segment joint, a joint bending test was conducted.

3.3.1 Outline of joint bending test

A scene from the joint bending test is shown in **Photo 1**. Two pieces of segments jointed together were supported on a platform with their ends kept free, and the joint was subjected to a bending test at a loading interval of 1,200 mm set so as to make the segment joint a pure bending section. The maximum bending load applied was a yield load calculated from the tensile yield strength of the bolt. The axial force introduced to the segment joint bolt was 80% of the allowable axial force.

3.3.2 Test results

Fig. 9 shows the relationship between the joint bending moment, calculated from applied load, and the angle of joint rotation. In the figure, the curved line indicates the experimental values, the broken line indicates the average rotary spring constants when the moment was increased to the allowable limit, and the straight line indicates the joint spring constants calculated by using the following Equation (1) given in the “Guidelines on Structural Design of Linings of Tunnels Subject to Internal Water Pressure” (Advanced Construction Technology Center).

$$k_\theta = \frac{k_\theta^* \cdot EI}{r} = \frac{2.1 \times 51{,}563}{2.575} = 42{,}000 \text{ kN} \cdot \text{m} / \text{rad} \qquad (1)$$

k_θ^* : Non-dimensional rotary spring constant
EI : Flexural rigidity of segment
r : Radius of segment ring centroid

The measured average rotary spring constant up to the allowable bending moment nearly coincides with the rotary spring constant calculated using the above Equation (1). Therefore, in segment design based on a beam-spring model that assumes the segment as a beam and the segment joint as a rotary spring, it is considered possible to use the rotary spring constant obtained from Equation (1). Even when the load applied was increased to the bolt yield strength, no decline in rigidity was observed and the bolt axial force that was separately measured demonstrated a linear increase. Thus, it was confirmed that the composite CP segment joint had sufficient load-bearing capacity.

4. Development of Composite CP Segment (Light-duty Type)

4.1 Characteristics of segment structure

The light-duty composite CP segment is a segment for tunnels having a smaller circumferential bending/axial force ratio than the heavy-duty version. It has the following characteristics.

(1) Since the segment is subject to relatively large axial compressive forces, the segment structure has been simplified: as few vertical ribs and main reinforcing bars as possible are arranged in a five-sided steel shell.

(2) Thanks to the load-dispersing effect of the curved skin plate and vertical ribs, the reinforced concrete and steel shell behave as a single composite structure against earth and water pressures.

4.2 Segment structural characteristics and design method

A bending test was conducted using surface load in order to study the segment’s structural characteristics in the ground when distributed loads, such as earth and water pressures, act upon the segment and to verify the design method.

4.2.1 Outline of bending test using surface load

As shown in **Fig. 10**, surface loads were applied to a full-scale segment test piece via a hydraulic bag (1,200 mm wide, 650 mm long) installed on the center of the span. After the maximum surface load was confirmed, it was applied to the capacity of the test apparatus.

4.2.2 Test results

(1) Flexural yield strength

The measured and calculated values of maximum flexural yield strength are shown in **Table 2**. **Fig. 11** shows the relationship be-

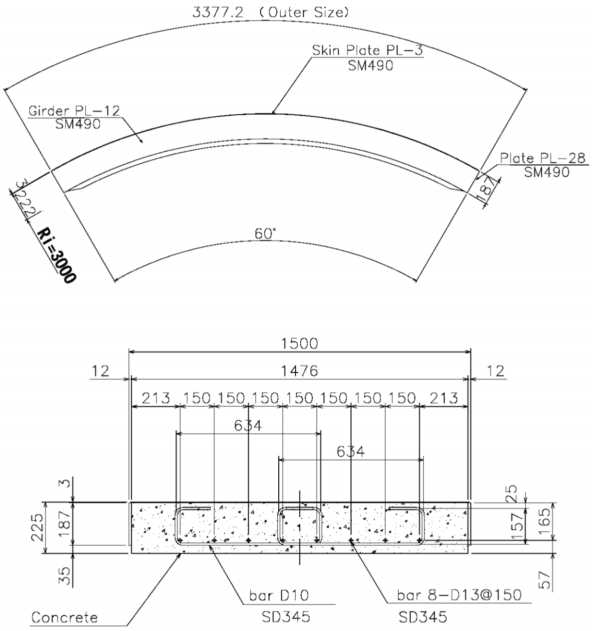


Fig.10 Specimen of composite CP segment for light loading

Table 2 Calculated and measured maximum moment

	Effective width of skin plate	Calculated		Measured
		RC	S	
Maximum Moment (kN• m)	All	200 (0.98)	144.6 (1.36)	196.2
	25 times at each girder	182.2 (1.08)	87.0 (2.25)	

* Values of inside brackets are measured monent - caluculated moment ratio.

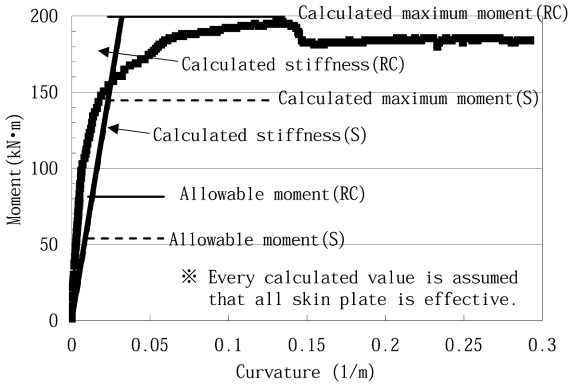


Fig.11 Relationship between moment and curvature

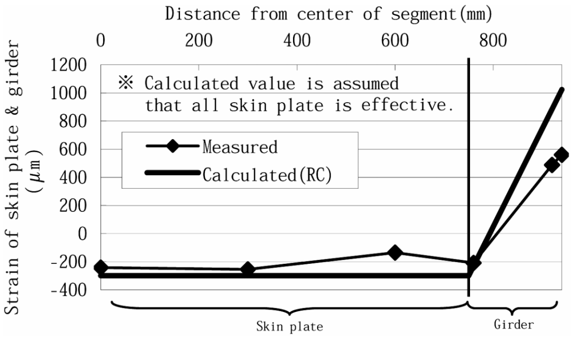


Fig.12 Strain distribution of skin plate and girder (at 79.2kN• m)

tween curvature and moment, obtained from the stain in the steel at the center of the test piece, and the calculated values of flexural yield strength and flexural stiffness for the reinforced concrete and steel structure. In both calculations for reinforced concrete (RC) and steel structure (S), two different cases were considered. In one case, it was assumed that the entire skin plate width was effective. In the other, it was assumed that the skin plate thickness multiplied by 25 was effective. The measured value of flexural yield strength was 196 kN·m. This is close to the ultimate flexural yield strength (200.0 kN·m) obtained by the RC calculation based on the assumption that the entire skin plate width was effective, whereas it was 1.36 times the totally plastic flexural yield strength (144.6 kN• m) obtained by the steel structure calculation based on the same assumption.

(2) Deformation characteristic

The measured values of flexural stiffness nearly coincided with the RC calculated values based on the assumption that the entire skin plate width was effective (see Fig. 11). Even after the test piece displayed its maximum yield strength, it demonstrated high deformation performance.

(3) Strain distribution in skin plate and main girder

Fig. 12 shows the distribution of circumferential strain in the skin plate and main girder across the segment width (at 79.2 kN·m: allowable load for RC design). It was confirmed that the distribution of skin plate strain was almost uniform across the segment width and that the measured values of strain nearly coincided with the RC calculated values based on the assumption that the entire skin plate width was effective.

4.2.3 Conclusion

It is considered that the light-duty composite CP segment has high deformation performance and that the ultimate flexural yield strength and stiffness of the segment can be RC-designed based on the assumption that the entire skin plate width is effective.

5. Application Example

5.1 Neyagawa Basin Sewerage Chuo (1) Expansion Trunk Line (2nd Section) in Osaka Prefecture

As an example of construction work applying the heavy-duty composite CP segment, this section describes the Neyagawa Basin Sewerage Chuo (1) Expansion Trunk Line (2nd Section) in Osaka Prefecture (contractor: consortium of Obayashi Corp., Kumagai Gumi Co., Asunaro Aoki Co., Fukuda Corp. and Daitetsu Kogyo Co.) scheduled for completion in August 2007 (see **Photos 2, 3 and 4**). This shield tunnel is constructed relatively deep in soft ground as shown in **Table 3**. In view of the properties of the ground through which the tunnel passes, the segment design is based on the total ground pressure. Under this load condition, the heavy-duty composite CP segment permits reducing the segment height to 60% to 70% as compared with when the RC segment is used. From the standpoint of cutting the total cost of construction, it was judged economical and rational to employ the heavy-duty composite CP segment. **Table 4** shows the principal specifications of the segment.

Up until May 2007, neither harmful cracking/breaking of the packed concrete nor leakage of groundwater due to jack thrusts during construction work or shocks during assembly work has occurred

Photo 2 Composite CP segment without concrete

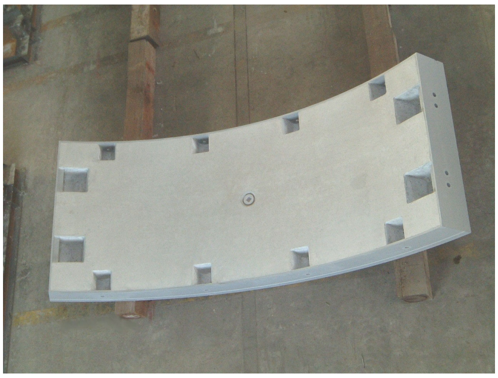


Photo 3 Product of composite CP segment

Photo 4 Shield tunnel constructed with CP segments

Table 3 Ground condition of shield tunnel

Tunnel outside diameter (m)	5.4
Length (m)	2 250
Depth (m)	25-30
Ground property	Soft clay
Representative SPT-N value	5

Table 4 Specifications of composite CP segment for heavy loading

Segment height (mm)	250
Segment width (mm)	1 200
Main girder thickness (mm)	16
Skin plate thickness (mm)	3
Steel bar positioned inside	D29×10
Steel bar positioned outside	D29×10

because the segments are covered in a steel shell. The segments are also easy to assemble. Tunnel construction is progressing smoothly at a pace of 10 rings (12 m) per day.

6. Conclusion

In view of the utilization of underground resources for urban renewal, such as construction of subterranean traffic infrastructure, it is considered that the underground space required in the future will be constructed deeper and on a larger scale, and that the segments for tunnel linings will be required to have not only higher cross-sectional performance, but also longer service life, better water-tightness and various other performances. We believe that the composite CP segments described in this paper will meet those requirements and greatly help promote the utilization of deep underground resources. We intend to continue making improvements to the composite CP segment to meet changing public requirements in cooperation with people from various quarters.

Acknowledgments

In developing the composite CP segment, Jun Koizumi, professor at the Department of Civil and Environmental Engineering, the School of Creative Science and Engineering of Waseda University, greatly helped us to establish the segment structure and design method. The authors wish to express their great appreciation for his support.