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# New Mechanical Joint Segment Tunnel Lining System

Minoru NAKAMURA[*1] Takashi YAMAGUCHI[*1]
Noriyuki HIROSAWA[*2] Kiyoshi NISHIDA[*2]

## Abstract

*After the Second World War, as the construction of the social infrastructure such as water supply and sewage systems, communications cables, railway and road networks advanced with urban sprawl, shallow underground installations have become congested, necessitating the use of greater-depth underground tunnels. To meet this change in construction environment, we have developed a new one pass lining system. This is the world's first boltless, mechanical joint segment (NM segment) system, which strengthens tunnel lining materials, assures water-tightness and facilitates automatic segment assembly. Since the technical performance of NM segment was demonstrated in the Neyagawa a River Underground Diversion Construction Project, its application is expanding from rivers underground diversion to railway tunnels. This paper reports on the development of the NM segment structure and describes the performance evaluation based upon actual application.*

## 1. Introduction

About 80% of Japan consists of mountainous regions. In the lowlands amounting to 20% of the total land area, office buildings and residences are concentrated in urban districts. Most of these urban districts exist in alluvial formations for forming fans.

With urban sprawl and the expansion of residential areas into the suburbs, the construction of the social infrastructure including water supply and sewage systems, communications cables, railway and road networks has advanced. The construction of the infrastructure was initially carried out by a ground open cut method. In recent years, however, traffic congestion and building construction on the ground have gradually made it difficult to employ this method. In urban areas in particular, the use of a tunneling method has begun. Including the urban NATM (New Australia Tunnel Method) and a shield tunneling method, this method is known generically as an urban tunneling method. Generally, urban NATM is used for a highly solid foundation while the shield tunneling method is used for a soft foundation. Both of these methods have been improved to suit the Japanese environment after the technology was introduced from Europe.

The shield tunneling method is used for constructing a tunnel by joining one block, called a segment, to another in drilling performed by a shield machine progresses and then forming a lining. Bolts and nuts have been used for joining the blocks.

A prototype of the shield tunneling method is a method for drilling earth and sand on the full surface of the ground by human power or the like while applying air pressure to a cutting face. This method was invented by a Frenchman named Bruner in 1818, and was first applied to construct a tunnel at the bottom of the Thames River in London. Later, it was improved to become the current hermetic shield tunneling method for preventing landslides by applying pressure to the cutting face by the shield machine to counter underground water pressure. Further, in recent construction, with the advance of automatic operation, a series of processes including machine control, segment transportation, assembling and drilled earth and sand transportation has been computerized.

*(1) Construction & Architectural Materials Development & Engineering Service Div.

*(2) Technical Development Bureau

## 2. Trend of Shield Tunnel Construction and Technical Problems

In urban areas the construction of building foundations and other infrastructures has caused shallow underground installations to become congested. Thus, effective utilization of deep underground areas has been advocated, and drafting of the Utilization of Deep Underground Space will be finished shortly. The National Land Agency published "Interim Report of the Provisional Investigation Committee for Deep Subterranean Utilizaiton (fiscal 1997). It can be expected that in future shield tunnel construction, deep underground areas will provide greater depth and longer distances for tunnels.

On the other hand, as part of the government's effort at financial reform, a reduction in public works spending has been advocated. The Ministry of Construction published the "Action Program for Public Works Cost Reduction" in fiscal 1997 in which a minimum 10% reduction in public works costs was set as a numerical target.

As apparent from these trends, in future public works projects, a shorter work period, automatic operation and a maintenance-free system (for long-term durability) will be necessary. Further, it can be expected that technology for to reduce construction costs will have to be developed.

## 3. Structural Characteristics of Boltless New Mechanical Joint Segment (NM Segment)

The NM segment was developed for constructing a high-quality tunnel based on a primary-lining segment system. High-quality means the "long-term durability" of the tunnel. Its structural characteristics are based on automation specifications for efficient assembly, reduced human labor and safe operation. Strengthening of tunnel lining materials, assurance of high water-tightness and heavy duty coating are also included in the specifications.

According to the specifications, the structure of the NM segment is a (1) boltless, (2) composite structure, (3) using NM shaped steel with a caulking groove and (4) a steel face heavy duty coating. Characteristic (1) facilitates automatic construction, characteristic (2) provides a high-strength member utilizing the combined characteristics of steel and concrete, and characteristic (3) provides high shearing performance and high water-tightness by engagement between the steel frames. Characteristic (4) provides long-term durability. **Fig. 1**[1)] shows the structure in outline.

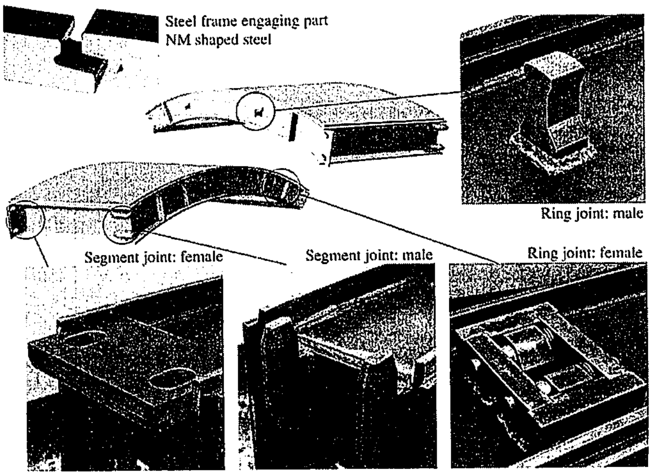



**Fig. 1 Secondary lining segment system omitted segment: Outline of structure of boltless NM segment (New mechanical joined segment)**

## 4. Development of Segment Main Body Structure and Joints

### 4.1 Structural behavior of segment main body as composite structure girder member

The NM segment has a composite structure created by (1) the confined effect of filler concrete by H-shaped steel frames on four sides and (2) the shear connection effect of the vertical ribs welded to the circumferential main beams and skin plates. This report introduces an example of a bending test using a relatively thin (250 mm thickness) actual size sample which verifies that a steel material and concrete can produce an integrated effect.

**Fig. 2** shows a sample and the testing method. **Table 1** shows the comparison of load-carrying capacities as testing results. **Fig. 3** shows the relationship of load-deflection. **Fig. 4** shows the relationship of load-strain. The experiment confirmed high ductility, and the maximum load of this time exceeded the ultimate bending capacity of the composite structure mode 7 by 16% and more. Flexural rigidity and steel material distortion both coincided well with the calculated values for the composite structure model.

### 4.2 Development of thin and wide segment – structural behavior as composite structure flexural plate member against surface load

The targets of the development were to develop thin NM segments for lower limit applications (expansion of application to tunnels having relatively small section forces) and wide NM segments for rapid construction and cost reduction. The load-carrying behavior of the composite structure had been identified for shape dimensions up to a segment thickness of 250 mm and a segment width of 1,200 mm in the past. Thus, in the new developments, a thin and wide segment having a thickness 200 mm and a width of 1,500 mm was set as the target. The increase in thickness and width brought about a reduction in the confined effect of the filler concrete provided by the H-shaped steel frames. Thus, there was concern that following the reduction of the confined effect, (1) a reduction in in-

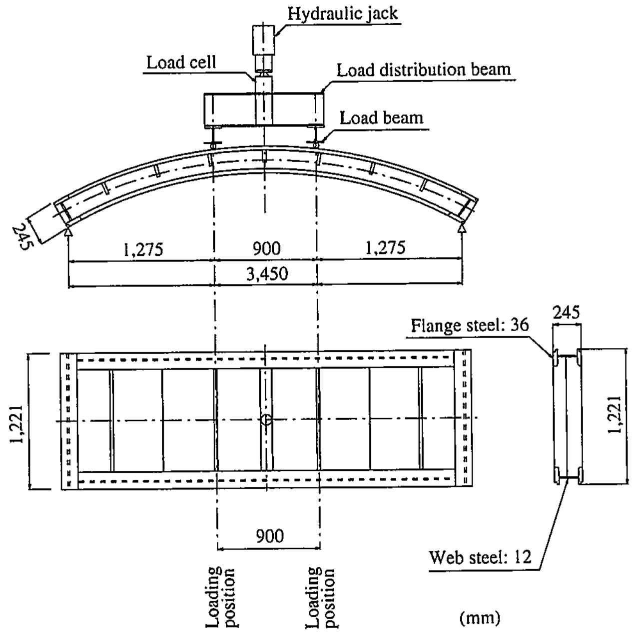



**Fig. 2 Outline of bending test**

**Table 1 Comparison of bending test load-carrying capacities**

| Experiment value :P1 (kN) | Calculated value: Composite structure model:P2(kN) | Calculated value: Steel structure model: P3(kN) | P1/P2 | P1/P3 |
|---|---|---|---|---|
| 1,617 | 1,396 | 1,239 | 1.16 | 1.31 |

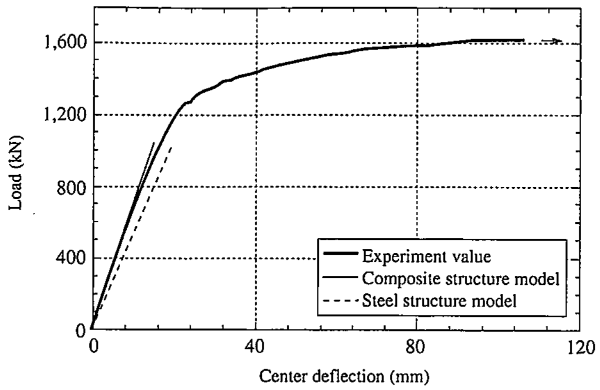



**Fig. 3 Bending test: relationship of load-deflection**

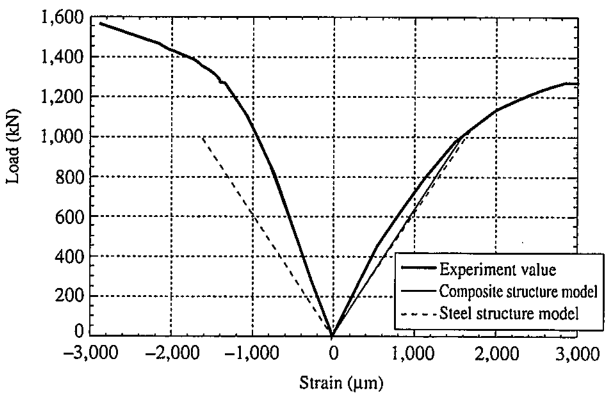



**Fig. 4 Bending test: relationship of load-strain**

tegrated performance of the steel frame and the concrete and (2) a reduction in the load-carrying capacity of the filler concrete flexural plate member against a uniform surface load (earth water pressure) would occur.

Thus, four NM segment mock flat plate samples including two segment widths of 1,200 and 1,500 mm and two with and without reinforcements were prepared. Using these samples, a bending test under uniform surface load by a water pressure tube simulating earth and water pressure was carried out (**Fig. 5**). Then, a comparison was made as to the load-carrying behaviors of their composite structures.

**Table 2** shows the comparison of load-carrying capacities, and **Fig. 6** shows the relationship of load-deflection. For the specimens (1.2N and 1.5N) without reinforcements, an opening and a level difference occurred between a main beam lower flange and the filler concrete upon initial loading, and these increased with the loading. This increase resulted in a reduction in integrated performance of the steel frame and concrete, and the falling of the filler concrete blocks immediately after the yielding of the main beam lower flange. Consequently, ultimate bending capacities were not provided for the composite structures.

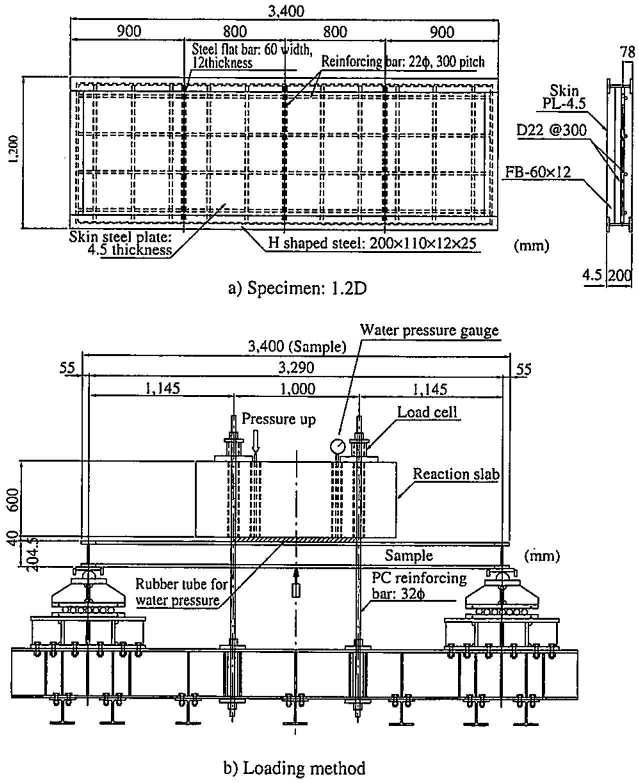



**Fig. 5 Outline of surface load bending test**

**Table 2 Comparison of surface load bending test load-carrying capacities**

| Specimen name | Width (mm) | Reinforcement | Experiment value (kN) | Composite structure calculated value(kN) | Experiment value / Calculated value |
|---|---|---|---|---|---|
| 1.2N | 1,200 | None | 512.2 [0.428] | 633.1 [0.528] | 0.81 |
| 1.5N | 1,500 | None | 518.2 [0.345] | 645.8 [0.431] | 0.80 |
| 1.2D | 1,200 | Exists | 784.2 [0.653] | 675.5 [0.563] | 1.16 |
| 1.5D | 1,500 | Exists | 784.8 [0.524] | 713.4 [0.476] | 1.10 |

Note: Value in [ ] indicates surface load (MPa)

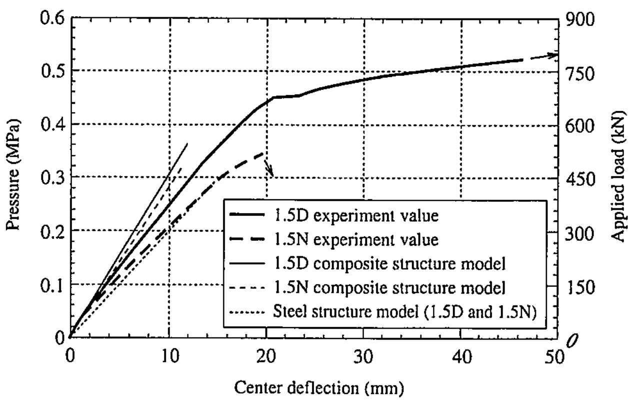



**Fig. 6 Surface load bending test: relationship of load-deflection**

The occurrence of the opening and the level difference may be attributed to the distortion of the main beam, punch shearing and transverse bending. For the specimens (1.2D and 1.5D) with reinforcements, the effect of the transverse reinforcements suppressed the distortion of the main girder, and simultaneously improved resistance to punch shearing and transverse bending. Thus, no openings and level differences occurred. For this reason, a capacity exceeding the ultimate bending capacity of the composite structure mode 7 was provided. It can thus be understood that by connecting both main beams with transverse reinforcements, even if the segments are made thin (200 mm segment thickness) and wide (1,500 mm segment width), (1) integrated performance can be secured and (2) a sufficient load-carrying capacity is provided for a filler concrete flexural plate member.

### 4.3 Bending under axial force of circumferential joint between segments using mechanically inserted male and female steel fittings

A conspicuous characteristic of the NM segment is its boltless automatic construction. The circumferential between segments has a unique structure using mechanically inserted male and female steel fittings. For application, it was important to evaluate the coefficient of rotational rigidity of the joint designed for each application situation. In particular, since it was necessary to identify any changes in joint behavior before and after joint mortar hardening and unravel the joint behavior when inner pressure was applied (application of circumferential direction tensile axial force) in the river underground diversion tunnel, a joint bending test was carried out under various axial forces.

In this test, as shown in **Fig. 7**, four-point bending was performed after a constant axial force was applied by hydraulic jacks via steel beams. **Fig. 8** shows the testing result of the relationship of bending moment and joint rotational angle. It was found that the cicumferential joint between segments under the application of a compressed axial force showed high rotational rigidity near tight coupling irrespective of the existence of the filler mortar, and the rotational rigidity of the joint between segments under the application of a tensile axial force can be evaluated using a nondimensional coefficient of rotational rigidity. **Fig. 9** shows the relationship of load-deflection. The ultimate bending capacity of the joint between the segments under the application of an axial force coincided well with the calculated result of a reinforced concrete model which was made by replacing the mechanical joint with a tensile spring.

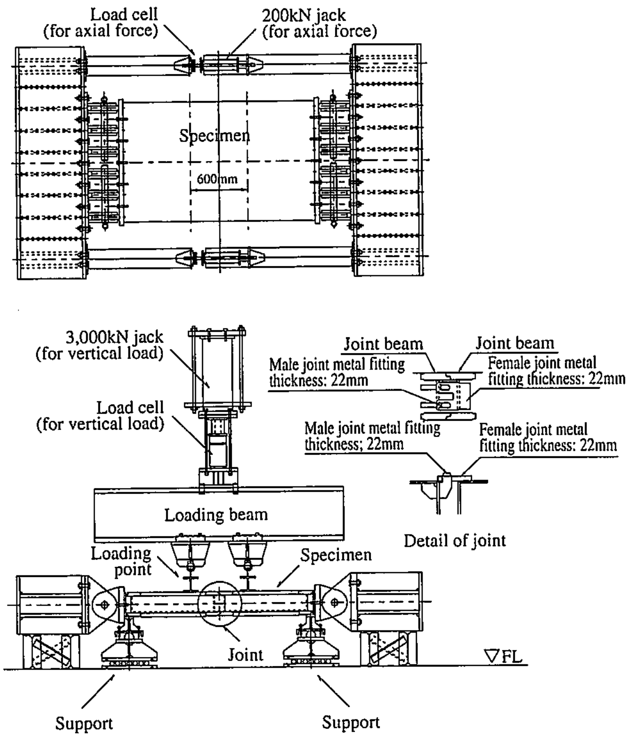



**Fig. 7 Outline of joint bending test under constant axial force**

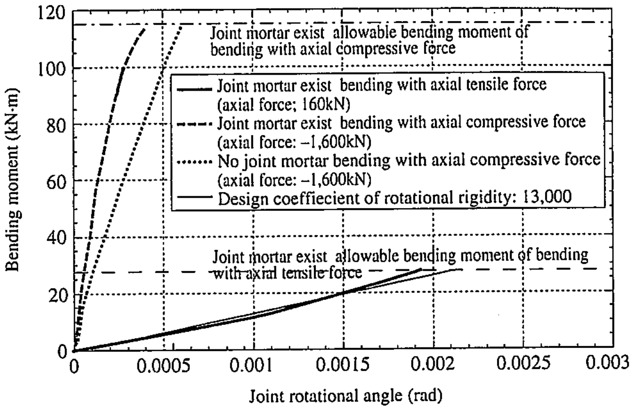



**Fig.8 Joint bending test under constant axial force: relationship of moment-joint rotational angle**

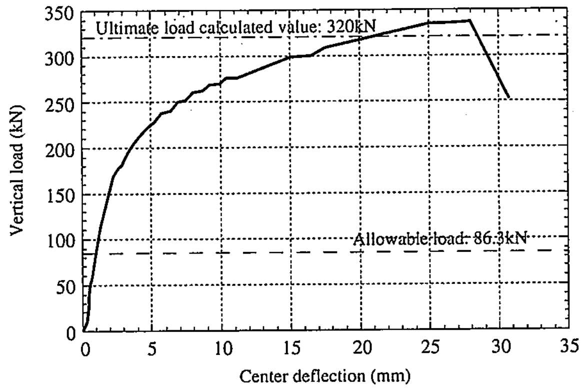



**Fig. 9 Joint bending test under constant axial force: Relationship of load-deflection**

## 5. Development of Corrosion Prevention Specifications for Tunnel Interior Steel Surfaces

### 5. 1 Necessity of corrosion prevention technology

River underground diversion tunnels are expected to function as rainwater discharge channels in the future. The tunnels completed sections can serve temporarily as a storage pond for controlling the water level of the river. Conventionally, primary and secondary lining segment systems have been employed in the lining specifications for river underground diversion tunnels. As will be described in the next section, however, since the NM segment employs a new one pass lining system, including both primary and secondary lining segment systems, it is subjected to the direct effects of the stored water.

### 5.2 Corrosion prevention of tunnel interior steel surfaces

Concerning the corrosion prevention specifications of tunnel interior steel surfaces for the lining segment system completed by the one pass lining system in the construction of river underground diversion tunnels, the Technical Research Institute Advanced Construction Technology Center set the basic specifications to be "epoxy primer + resin mortar" which was proven to be effective as interior surface specifications for sewage systems. Thus, for the development of corrosion prevention specifications, an optimization process was started based on the basic specifications. The environments were estimated as follows:

(1) No paint degradation caused by sunlight occurs in a river underground diversion tunnel.
(2) Water flowing in is mainly rainwater and it is stored, thus the amount of dissolved oxygen is low.
(3) Abrasion may occur by quicksand.
(4) It is possible to gauge lining segment deformation caused by external or internal pressure or segment weight.

Specifically, the degradation factors of the painted interface were extracted, and these factors decided the paint adhesion and corrosion prevention specifications of the paint shown in **Table 3**. **Fig. 10** shows the painted interface.

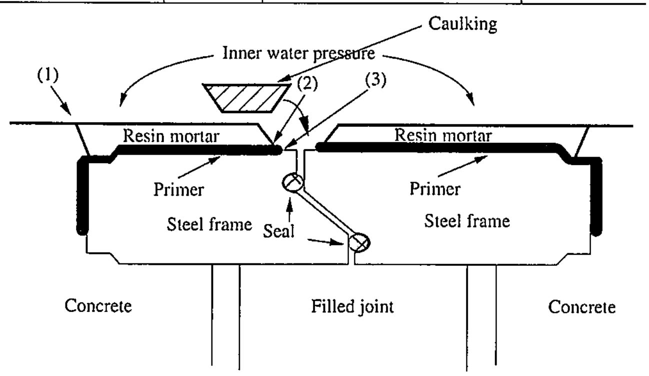
### 5.3 Establishment of testing method and evaluation test

The one pass lining system for a river underground diversion tunnel construction is a novel technology, thus almost no examples of using steel materials can be found. Therefore, a new testing method had to be established for evaluation.

The degradation of the painted steel interface was caused by a reduction in adhesion with the steel surface under a wet and dry, immersion or wet environment, and the degradation of the paint itself was possibly caused by the occurrence of cracks upon deformation or abrasion by quicksand. Thus, optimization of the shapes of the sample and the testing conditions was examined and an accelerated corrosion testing method was established. For an abrasion test, a drying type drop and impact tester was invented. Further, to investigate the efficiency of painting workability, the level of brushability for the paint film after painting and the existence of sagging for the paint film (tested by inclination of 25°) were inspected. **Fig. 11** shows partial results of the paint adhesion test. For comprehensive evaluation, comparison was made for such factors as (1) paint film property, (2) deformation property, (3) chip resistance, (4) alkali resistance, (5) acid resistance, (6) wet adhesion, (7) corrosion resistance and (8) painting workability, and then optimal specifications were selected. **Table 4** shows partial results of the evaluation test.

**Table 3 Degradation factors of painted interface**

| Degradation part | Classification | Factor | Existence of problem |
|---|---|---|---|
| Paint film itself | Physical | Sand | Exist |
| | | Heat | None |
| | | Deformation | Exist |
| | | Impact during execution | Exist |
| | Chemical | Light (ultraviolet rays) | None |
| | | Chemicals (alkali/acid) | None |
| | | Water | Exist |
| Painted interface | Chemical | Water | Exist |
| | | Chemicals (alkali/acid) | Exist |
| | | Oxygen (corrosion) | Little |




Interface (1); Resin mortar/concrete
Interface (2): Primer/resin mortar
Interface (3): Primer/steel frame

**Fig. 10 Corrosion prevention layer section of NM segment**

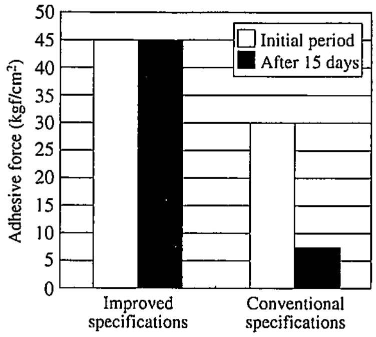



**Fig. 11 Difference in adhesion between corrosion prevention specifications by immersion test with temperature inclination**

**Table 4 Evaluation result**

| Testing content (Specifications / Surface penetration) | | | Improved specifications, Surface penetration class-1: Primer | Improved specifications, Surface penetration class-1: Resin mortar |
|---|---|---|---|---|
| Deformation | Identification of abnormality when 10 mm deformation is given to a length of 300 mm | | No abnormality | |
| Chip resistance | Drop and impact test (ASTM5/16 firing pin 2.5kg·m, 4kg·m) | | | No abnormality |
| Friction resistance | Abrasion test: Measure the wearing amount of sample piece 3 hours after 25g of abrasives are dropped to sample piece from height of 1m by 30 times/min. | Abrasives | | GP-7 (grid material) |
| | | Wearing | | ○ |
| | | Abrasives | | Sand#100 |
| | | Wearing | | ○ |
| Alkali proof | Immersion in 10% sodium hydroxide solution (3 weeks) | | No abnormality | |
| Acid resistance | Immersion in 10% sulfuric and solution (3 weeks) | | No abnormality | |
| Wet adhesion | Immersion test with temperature inclination*1 | Blister | ○ | ○ |
| | | Adhesion | ○ | ○ |
| | NaCl solution immersion test*2 | Rust progress | ○ | ○ |
| | | Adhesion | ○ | ○ |
| Corrosion resistance | Salt spray test*3 | Rust progress | ○ | ○ |
| | | Adhesion | ○ | ○ |
| | Dip and dry test*4 | Rust progress | ○ | |
| | | Adhesion | ○ | |
| | Dip and dry test after impact test | Existence of corrosion from impact stains | ○ | |
| Total evaluation | Individual comparison between primer and resin mortar | | ◎ | ○ |
| | Total evaluation | | ◎ Very good adhesion in immersion environment and very good corrosion resistance in wet and dry environment | |

*1 Testing condition: Pure water 40/15°C, primer (2 weeks), resin mortar (1 month)
*2 Testing condition: 40°C, 3% NaCl, 1 month
*3 Testing condition: 35°C, 3% NaCl, 1 month
*4 Testing condition: 1 hour 60°C drying, 1 month of repeating 1 hour 40°C dipping

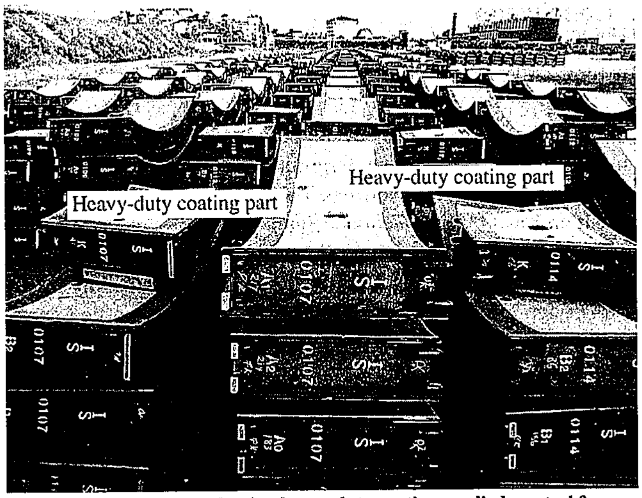



**Photo 1 NM segment having heavy duty coating applied on steel frame**

### 5.4 Corrosion prevention specifications for a river underground diversion tunnels

Basic corrosion prevention materials were improved, and a combination of the materials was selected. After evaluation by various tests, the corrosion prevention of the NM segment was found to satisfy the following specifications:

(1) To assure adhesion with the paint film, surface preparation class-1 (highest of 4 classes of surface preparation) should be used for the surface preparation of the steel surface.

(2) The epoxy primer material directly coated on the steel surface should show small blisters and little reduction in adhesion, even in the immersion test with temperature inclination (temperature difference of 25°C) of pure water.

(3) The resin mortar of the uppermost layer used also as a corrosion prevention material should have no paint exfoliation even under the deformation of 10 mm over a length of 300 mm, and should have abrasion resistance equal to that of concrete. A 5 mm thick coating should be achieved in one step.

The above specifications were actually applied for the construction of the Neyagawa North Region a River Underground Diversion, Furukawa Control Pond. **Photo 1** shows portions where heavy duty coating was applied for the steel frames of the NM segments.

## 6. On-site Construction

Neyagawa underground river

The construction of the NM segments for the Neyagawa North Region River Underground Diversion Furukawa Control Pond in Osaka Prefecture (joint venture by Kajima, Kumagai, Tobishima Kensetsu and Konoike, length 2 km, inner section 7.5 m, and tunnel bottom GL–48 m), based on the one pass lining system were finished in October 1997. In this project, set-up speed, out-of-roundness and complete water-tightness of the lining under design applied water pressure of 4 kgf/cm$^2$ were verified. The technology evaluation of the NM segment in this construction project expanded application fields to the construction of the Neyagawa South River Underground Diversion Kyuhoji Control Pond and a railway tunnel (Minato Mirai 21 Line). **Fig. 12**[2] shows the route of this construction, and **Photo 2** shows the tunnel inner section after application. Also, **Table 5**[3] shows the set-up of segments, and **Table 6**[3] shows the measurement of the tunnel inner section. All of these are superior to those of prior technology. The rolling of NM shaped steel and

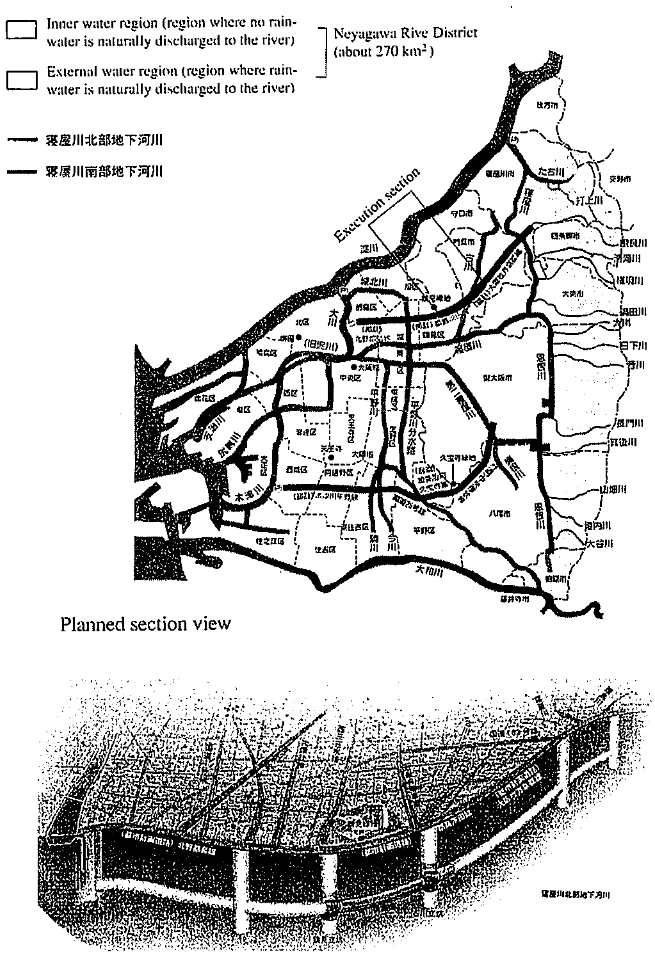



**Fig. 12 Outline of underground river route profile**

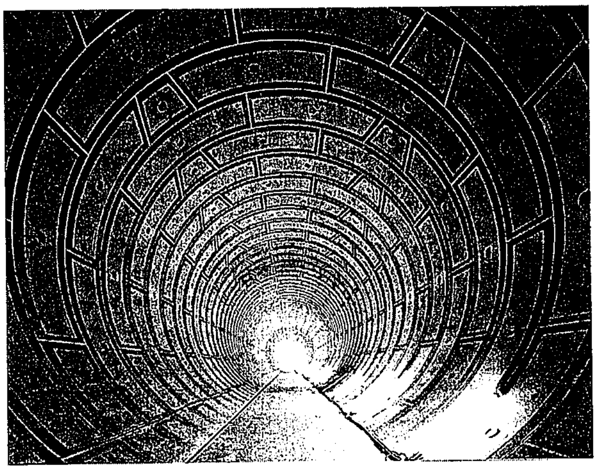


**Photo 2 Construction of Neyagawa North Region River Underground Diversion Furukawa Control Pond**

**Table 5 Segment arrangement time**[3)]

| Ring No. | Soil class*1 | Drilling time | Segment*2 | Manual Half-automatic | Arrangement time |
|---|---|---|---|---|---|
| 100 | Dc3·Dsg3 | 70 min | NM | Manual | 60 min |
| 200 | Dc3·Dsg3 | 60 min | NM | Half-automatic | 50 min |
| 300 | Dc3·Dsg3 | 80 min | NM | Half-automatic | 40 min |
| 600 | Dc3·Dsg3 | 60 min | NM | Half-automatic | 40 min |
| 885 | Dc3 | 50 min | DC | Manual | 120 min |
| 1,000 | Dc3 | 50 min | NM | Half-automatic | 30 min |
| 1,200 | Dc3 | 50 min | NM | Half-automatic | 30 min |

*1 Soil: Dc3→Dilluvial clay layer (N value 7 to 14)
Dc3·Dsg3→Dilluvial gravel layer (N value≥60)
*2 Segment: NM→boltless·8P
DC→Opening reinforcing special steel·10P

**Table 6 Measuring results of degree of lining circle section and tunnel inner section**[3)]

| | NM segment (general part) | Ductile (opening part) |
|---|---|---|
| Vertical dimension | −10mm - −16mm | −32mm |
| Horizontal dimension | +13mm - +6mm | Non measured |

highly accurate segment manufacture brought about these results. Lining complete water-tightness and steel surface heavy-duty coating technologies are expected to provide long-term durability for the tunnel linings.

In the conventional construction of a river underground diversion tunnels, lining specifications have been employed in which underground pressure and water pressure were dealt with in the one pass lining system of reinforce concrete, and inner pressure at the time of river water storing was dealt with the secondary lining segment system of inner reinforced concrete. From fiscal 1993 to 1994, the Advanced Construction Technology Center was entrusted by the Kanto Construction Agency, Tokyo Metropolitan Government and Osaka Prefectural Government to develop a novel "inner pressure type primary segment system" lining structure for completing inner and external load by a primary lining member. The center set up a technology committee including scholars and experts in the field, carried out various load tests and finally selected the NM segment as one of the key candidates. The construction was part of its extension.

## 7. Conclusion

It can be expected that the future construction of urban infrastructures will go much deeper underground. The NM segment was applied for the first time as the inner pressure one pass lining system in the construction of the very deep, long-distance drilling and large-diameter Neyagawa River Underground Diversion Tunnel, and its technological merits were verified. This verification was mainly dependent on Kashima application technology. The concept of boltless segments was provided by Yoshiji Matsumoto, professor emeritus of The University of Tokyo (currently of Science University of Tokyo). The application in Subway Loop 12 of the Tokyo Traffic Agency served as a starting point for the establishment of the one pass lining system technology. The authors wish to extend their gratitude to these organizations and individuals.

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