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# Structure and Construction Examples of Tunnel Reinforcement Method Using Thin Steel Panels

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## Abstract

***Recently, there have been many reports regarding tunnel structures where tunnel concrete lining has deformed (such as cracks, concrete flakes falling off and other types of deformation) due to external or internal factors such as aging, deformation of natural ground, and earthquakes. Therefore, going forward it will be increasingly important to provide proper repair and reinforcement to the tunnel lining, and consistently maintain and manage the tunnels. This paper introduces a method of reinforcing existing tunnel structure, called "Tunnel Reinforcement Method using Thin Steel Panels", whereby steel panels are processed to a shape which is similar to the tunnel inner lining and installed within the tunnel as reinforcement. Each panel is bilaterally joined utilizing houndstooth- arrangement. This method has been developed by combining steel- board reinforcement work used for reinforcement of aqueduct tunnels and steel segment technology used for shield tunnels. We will introduce this method in this paper.***

## 1. Introduction

In recent years, troubles with the concrete linings of tunnels, such as exfoliation, cracking and deformation due to aging, terrestrial transformation, earthquakes or other internal or external factors, have been reported from various parts of the country. Therefore, maintaining and managing tunnels on a continual basis while making the necessary repairs and reinforcement of their concrete linings have become important tasks both for the present and the future. In particular, the repair/reinforcement methods that are applied to railway and road tunnels must be such that the work can be carried out safely without interfering with traffic since railways and roads are the principal infrastructure for transportation. This paper will introduce a new tunnel reinforcement method that is applicable to both railway and road tunnels. This method permits speedily constructing a thin-walled reinforcement lining by applying pieces of steel plate (hereinafter referred to as "panels") to the existing tunnel lining.

## 2. Characteristics of the New Tunnel Reinforcement Method

### 2.1 Characteristics and position of this method

In this method, panels made of steel plate 8 to 20+ mm in thickness are applied to the inner surface of the tunnel to be reinforced. Their shapes are adjusted by utilizing a bar-like member ("spacer") to secure an appropriate gap between the panel and the existing lin-

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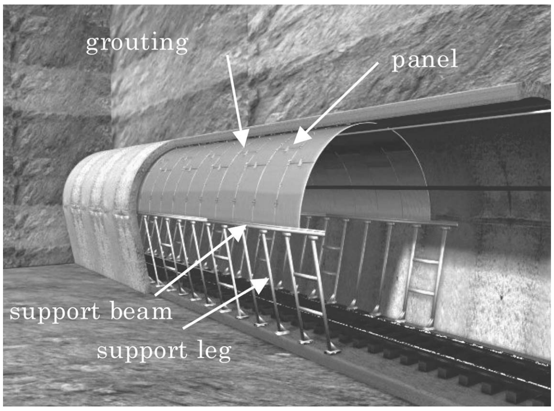



**Fig. 1 Image of basic structure**

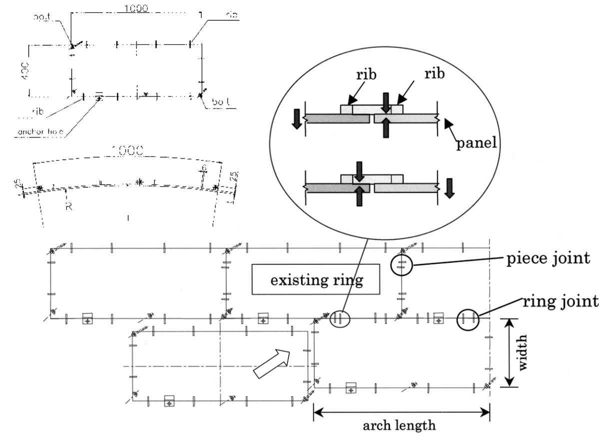



**Fig. 2 Panel details and assembling method**

ing. Then, the gap is filled with grout. Thus, this reinforcement method can be applied to prevent exfoliation of concrete lining, restrain ground disturbance, etc. (**Fig. 1**). The salient characteristics of this method are enumerated below.

1) Thin-walled structure: A reinforcement structure that is made up of panels can be worked into the desired shape according to the existing lining. Therefore, even where there is only a narrow space between the restriction boundary of a building and the existing lining, it is possible to construct a thin-walled reinforcement lining which does not cause the tunnel inner section to change significantly.
2) Prefab method: Since the panels are assembled by fitting together steel members prefabricated at the factory, the accuracy of fabrication of members is high and the field construction work can be carried out accurately. In addition, the panels are highly corrosion resistant.
3) High yield strength: Since the reinforcement lining is a freestanding arched structure constrained to the existing lining by grout filled in between the steel panel and the existing lining, it has high yield strength despite its limited thickness.
4) Permanent reinforcement measure: The freestanding structure mentioned above can be a permanent reinforcement measure when corrosion prevention appropriate to the tunnel environment is applied to it.
5) Speedy assembly work requiring no welding operation: Since the assembly of panels requires no welding operation, it can be done quickly even at midnight. Even during execution of the work, traffic through the tunnel is not impeded at all.
6) Smooth inner surface: The smooth inner surface of the reinforcement lining has aesthetic appeal and can easily be washed when stained.

**2.2 Types and features of this method**

In accordance with the structure of the lining and the method of construction, this method is divided into the following three types:

1) Large panel type: A single steel plate is installed circumferentially by mechanical power.
2) Medium-sized panel type: Medium-sized pieces of steel plate are installed circumferentially by mechanical power.
3) Small panel type: Small pieces of steel plate are manually installed circumferentially

(1) Characteristics of structure

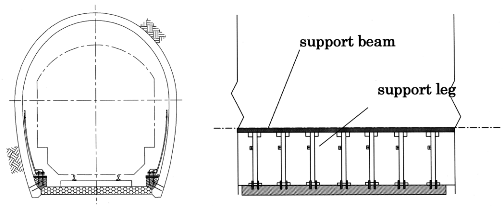
The large panel type can be applied to water conduits, etc., the existing lining of which is free of any installations. Here, we shall describe the medium-sized panel type and small panel type that are applicable to many different tunnels. The salient characteristic of the panel structure is that panels provided with ring joints along the long sides and piece joints along the short sides are arranged in a staggered manner and the panel load is supported by the steel plate and joints (**Fig. 2**).

Each type permits construction of a thin-walled reinforcement lining. Since the lining protrudes not more than about 50 mm toward the inner section, it can be installed even in locations subject to severe boundary restrictions from nearby buildings.

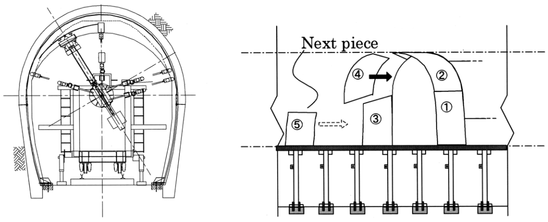
Like shield segments, the joints play a role in load transmission by their splicing effect. The external force can be supported by two or more rings.

(2) Characteristics of construction method

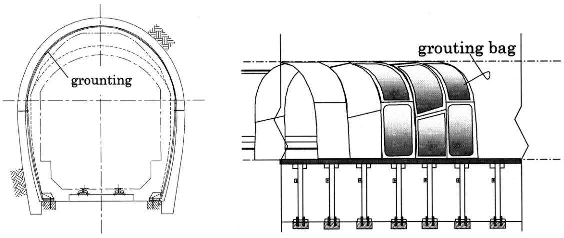
As an example, the work execution procedure when medium-sized panels are applied to a railway tunnel is shown in **Fig. 3**. The




**(1) Assembly of support leg and beam**




**(2) Installation of panels**




**(3) Grounting**

**Fig. 3 Installation process by elector machine**

panel size is 8 to 20+ mm thick, 1,000 mm wide and 2,000 to 3,000 mm long. A vehicle similar to the segment assembly vehicle employed in a shield tunnel is used to assemble the panels. It is equipped with a panel-holding mechanism (hereinafter referred to as the "erector"). The machine permits speedy assembly of the panels. When the small panel types are applied, they are assembled manually. Therefore, panels weighing less than 30 kg/piece are used. These panels are 8 mm thick, 400 mm wide and 1,000 mm long. This type can effectively be applied to tunnels which are too small to permit use of a construction vehicle.

## 3. Structural Characteristics and Design Method

### 3.1 Structural characteristics

The panels form an arched structure. As already mentioned, it is a freestanding structure constrained by the existing lining and surrounding ground via the grout filled in between the panels and existing lining. Therefore, even though the arched structure has limited wall thickness, it is capable of resisting external force applied by exfoliation of the existing concrete lining, ground disturbance, etc. With the aim of roughly determining the reinforcement effect of steel plates applied to an existing lining, calculations were performed with a basic structure in which a single steel plate of uniform thickness was applied to a concrete lining. The calculation results are shown in **Fig. 4**. In anticipation of exfoliation of the lining concrete or loose soil pressure, six cases were analyzed in which the steel plate thickness (t) was varied between 8 mm, 16 mm and 24 mm and the tunnel diameter (D) was varied between 5 m and 10 m under a distributed load (W), as shown in the figure.

In the analysis, it was assumed that each panel was a beam model and the ground spring was a nonlinear non-tension spring. As the compression-side spring constant (Kv), 50 MN/$m^3$–a value slightly on the small side–was adopted for sandy soil. The steel plate used was SM 490, and the load under which it reached the permissible stress ($\sigma_a$ was assumed to be 185 N/$mm^2$ in accordance with the Specifications of the Japan Road Association) was calculated. The calculation results show that, assuming the soil's specific gravity to be 18 kN/$m^3$, the structure can withstand loose soil pressure corresponding to loosening height 0.4 to 1.8 times the tunnel diameter (H = 4.81 to 8.81 m when D = 5 m; H = 3.95 to 8.17 m when D = 10 m).

### 3.2 Joint construction

The joints are of a mechanically fitting construction (Fig. 2). During panel assembly, the panels are clamped together by bolts which are installed obliquely to prevent the panel joints from opening axially or circumferentially. Flat bars are provided as joint members between panels, and in expectation of the splicing effect produced by enabling the panels to mutually constrain their displacement in the shear direction, the joint structure has been so designed that the radial shear force is transmitted to the adjoining rings and the adjoining panels within the same ring. As a result, each pair of facing ribs can transmit the shear force regardless of whether it is positive or negative (Fig. 2). Water cut-off sponge applied to the four sides of each panel restrains the leakage of water from between the panels.

### 3.3 Joint strength test

With the aim of determining the panel load-bearing characteristic and the joint strength characteristic, a loading experiment was conducted. The scene of the loading test is shown in **Photo 1**. The test pieces used were small panels (8 mm plate thickness × 400 mm width × 1,000 mm circumferential length; 4,200 mm R (steel plate outer surface)). From three rings of panels, a section (1,000 mm width, 2,000 mm circumferential length) was taken out and a variable concentrated load was applied to its center.

The test results are shown in **Fig. 5**. In the figure, the calculated values and measured values obtained by using a beam-spring model with the fitting joints as shear springs (described later; see **Fig. 6**) are shown. In the analysis, the panel deflection (δ) in the shear direction under load (P) was evaluated to set a shear spring constant (Kr = P/δ).

By varying the joint spring constant until the calculated value agreed with the measured value, the shear spring constant could be determined.

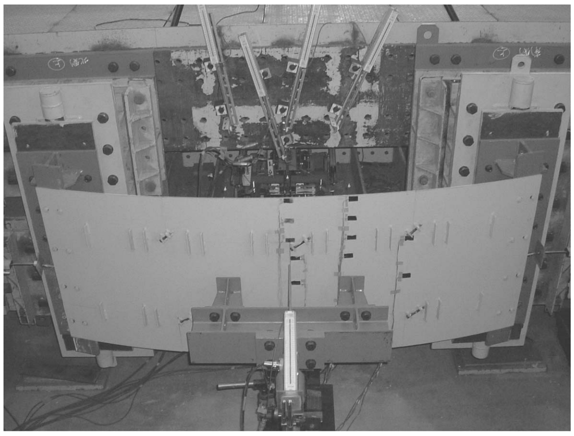


**Photo 1 Loading experiment**

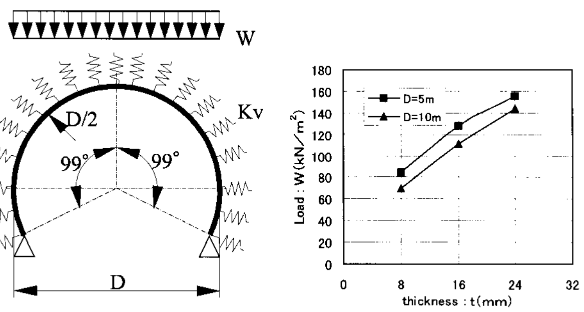



**Fig. 4 Calculation model and result**

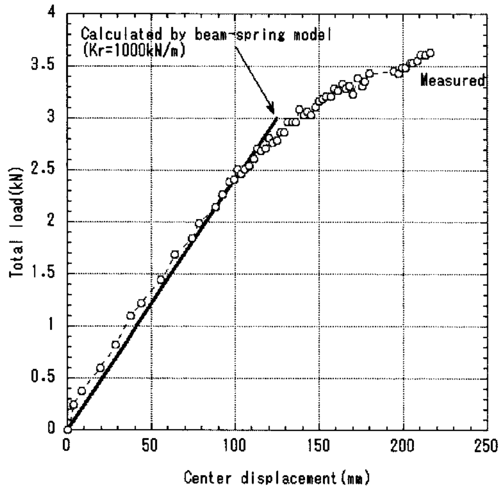



**Fig. 5 Comparison for experiment result and FEM analysis**

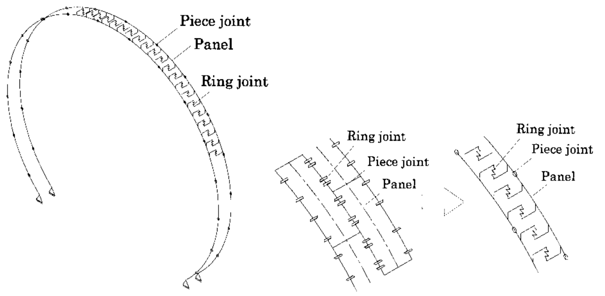



**Fig. 6 Frame-spring analysis model**

**3.4 Design method**

3.4.1 Structural models

(1) Structural models

In this design, based on the results of the above experiment, an analysis is made by using a beam-spring model, with the panel modeled as the circumferential beam model and the joints modeled as described below (Fig. 6).

(i) Ring joint

The ring joint is modeled as a radial shear spring. As the spring constant of the shear spring, the spring constant that was obtained in the above experiment is set.

(ii) Piece joint

The piece joint is modeled as a pin joint which transmits the axial force between circumferential panels (piece joint) but which does not transmit the bending moment between them.

(2) Ground spring

In the study made during the work, as the point-supported ground spring via the portion from the ground to the spacer in the radial direction, only a nonlinear, non-tension spring is considered.

In the study after completion of the reinforcement lining as a permanent structure, the reaction from the portion from the grout to the ground is considered. As the ground spring, a nonlinear, non-tension spring which is assumed as a distribution spring via the portion from the ground to the grout in the radial direction is considered.

3.4.2 Design load

After completion of the reinforcement lining, the panel weight, air pressure during the passing of a train (or motor vehicle), grout weight, exfoliation load and soil load are considered as the design load. During the work, consideration is given to the load that increases as the grouting process progresses.

## 4. Types and Methods of the Work

**4.1 Survey and design**

The cross-section shape of an existing tunnel is surveyed in detail by using an optical range finder or some other suitable instrument. This is to determine the relative positions of the existing lining and restriction boundary lines of adjacent buildings and to design a cross section of the panel installation that minimizes the decrease in tunnel cross section due to the reinforcement.

**4.2 Relocation of wiring, etc.**

As far as possible, the electrical wiring, communication/signal lines, lighting equipment, metallic supports, etc. that are installed in the tunnel lining need to be removed or relocated temporarily before commencement of the reinforcement work from the standpoint of securing the safety of wiring and facilitating the work.

**4.3 Installation of panel support legs and beams**

At the bottom end of the panel installation, a grooved beam into which the panel can be fitted in the axial direction of the tunnel is installed as a panel-supporting member. When panels are to be installed only in the upper part of the tunnel section, support legs up to the bottom end of the panel installation are erected on the ground and a panel-supporting beam is installed on those support legs. When support legs are erected, empty grout bags are previously placed behind them. After the panels are installed, grout is put into those bags to fill the gap between the existing and new linings.

**4.4 Panel installation**

When small panels are employed, the panels are manually brought to the installation location and assembled on a simple scaffold. The panels are continuously assembled in the circumferential direction of the tunnel using standard tools (e.g., wrenches). No special equipment is required for panel assembly. During panel assembly, the panels are temporarily fixed to the existing lining with furnished anchors in order to control the gap between the existing lining and the panel used for panel positioning and shape adjustment, and to prevent deformation of the panels during grouting.

When medium-sized panels are employed, the panels are positioned by a construction vehicle equipped with an erector (because they are heavier) and installed in the same way as mentioned above.

**4.5 Grouting**

The gap between the panels and the existing lining is filled with grout either directly or by means of bags. In the latter case, a bag is attached to the back of each panel before assembly and after all the panels are installed, grout is injected into the bags from the inside of the panels through the grouting holes. An ordinary cement-based grouting material whose spring stiffness is equal to or greater than that of the surrounding ground is used. Although direct grouting is the norm, grouting by means of bags may be selected depending on conditions at the construction site. The advantages of using bags for grouting are as follows.

1) Water which leaks from the lining can be drained through the gaps between bags.
2) An end plate to stop the flow of grout can be omitted.
3) Grout does not flow out through cracks, etc. in the lining.
4) Since leaking water does not mix with the grout, the grout quality is maintained for a prolonged period.

**4.6 Restoration of wiring, etc.**

After the work is completed, the metallic supports are refitted to the panels and the wiring, lighting equipment, etc. that have been relocated temporarily are reinstalled in their original positions.

## 5. Examples of Works Executed

**5.1 Work on subway tunnel**

Use: Single-track subway tunnel (constructed in 1963)
Tunnel inner section: Height H = 5.4 m, breadth B = 6.8 m
Length reinforced: 4 m (straight section)
Panel construction: Small panel (16 pieces/ring × 10 rings), t = 8 mm
Construction time: About 3 hours/day (from cessation of power after the last train until restarting prior to the first train)

The subway tunnel had a primary lining of concrete segments and a secondary lining of concrete applied to the primary lining. In this work, which was carried out as a measure to prevent the exfoliation of concrete of the secondary lining, panels were applied to the entire inner surface of the existing tunnel lining for a length of 4 m. The method used was the small panel type and the panels were assembled and applied manually. Since the wiring inside the tunnel

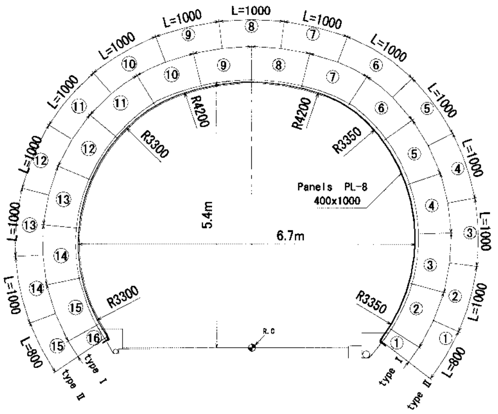



Fig. 7 Panel arrangement for tunnel section

Photo 2 Example of construction for subway tunnel

could not be relocated to the ground, the metal fittings for the wiring were replaced with smaller ones to secure adequate clearance from the existing lining for insertion of the panels. The inner section of the tunnel and the cross section and the reinforcement lining are shown in **Fig. 7**.

By using a construction vehicle equipped with a scaffold capable of being moved up and down, the work progressed at a pace of 2 to 3 rings per day.

Grout was directly injected into the open space behind the panels without using bags. A 5 mm-thick sponge pad was sandwiched between panels to stop water leaks. It has been confirmed in laboratory tests that the sponge prevents grout leakage even up to pressures of 0.2 MPa.

The panels could be installed with a high degree of precision, with the cross-section shape after the work showing only about a 5 mm margin of error from the design dimensions (**Photo 2**).

**5.2 Work at road tunnel**[1)]

Use: Road tunnel with 2 lanes in each direction
(constructed in 1973)
Inner section: Height H = 6.4 m, breadth B = 9.9 m
Length reinforced: 40 m
Panel construction: Medium-sized panels (9 pieces/ring),
t = 24 mm
Construction time: About 8 hours/day
(two lanes blocked alternately)

This work was carried out as a measure to reinforce the tunnel lining so as to prevent deformation under the ground load and other loads applied to it from above. The tunnel was a structure bearing the vertical load of a 9 m-thick overburden. The construction method used was the medium-sized panel type and the panels were applied by mechanical power. The cross sections of the tunnel and reinforcement lining and the work execution procedure are shown in **Fig. 8**. The panels are made from SM 490, each measuring 1 m × 2 m and weighing 400 to 500 kg. An erector machine equipped at the front end with a hydraulic adjustment jig for fine adjustment of panel positions (**Photo 3**) was used to facilitate panel handling and speed up panel assembly. As a result, the work progressed at a pace of about 1 ring per day despite the fact that the two lanes were blocked alternately to avoid a complete shutdown of traffic. In addition, at the construction site, efforts were made to reduce temporary installations and workspace in order to minimize the impact on the environment (**Photo 4**).

**5.3 Other examples of work executed**

(1) Road tunnel (**Photo 5**)

Use: Road tunnel with one lane in each direction
(constructed in 1930)

Photo 3 Installation of panel by elector machine

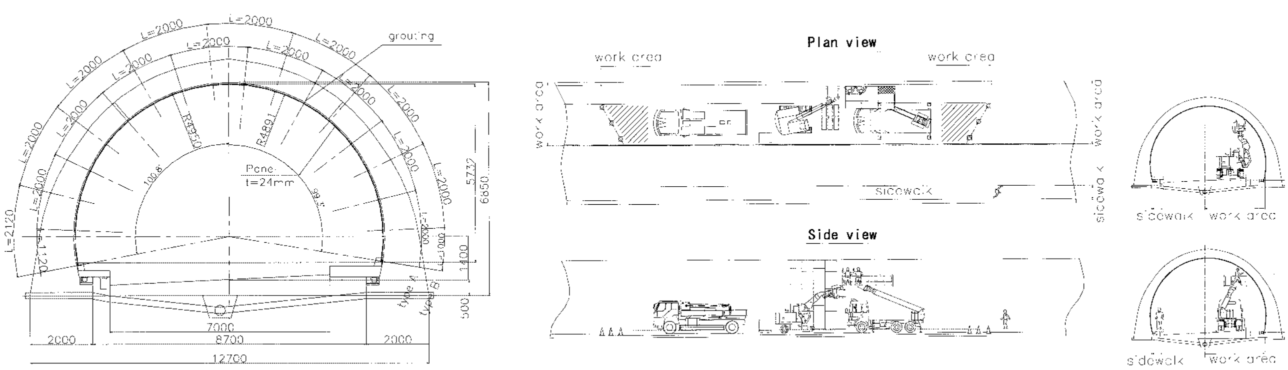



Fig. 8 Section design and installation of panel

**Photo 4 Completion**

**Photo 5 Example of road tunnel**

Inner section: Height H = 6.5 m, breadth B = 9.0 m
Length reinforced: 75 m
Panel construction: Small panel (16 pieces/ring), t = 8 mm

(2) Railway tunnel (**Photo 6**)
Use: Conventional, non-electrified, single-track railway tunnel (constructed in 1933)

**Photo 6 Example of railway tunnel**

Inner section: Height H = 5.2 m, breadth B = 4.6 m
Length reinforced: 31 m
Panel construction: Small panel (support legs + 8 panels/ring), t = 8 mm

## 6. Conclusion

It has been demonstrated that the method described above permits the speedy and safe construction of a reinforcement structure even in locations where the restrictions from buildings are severe. Thus, it is possible to establish a new, permanent measure to rehabilitate tunnel structures. We hope that our method will be applied to many different tunnel structures in the future.

**Acknowledgments**

We wish to express our heartfelt gratitude to Mr. Yoshiji Matsumoto, professor emeritus at the University of Tokyo, for his generous cooperation in establishing this new structure and construction method.

**References**

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