RESEARCH AND DEVELOPMENT ON THE SEISMIC ISOLATION SYSTEM APPLIED TO URBAN TUNNELS (PART-1: DEVELOPMENT OF SEISMIC ISOLATION MATERIALS AND CONSTRUCTION METHODS)

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ABSTRACT

Techniques for improving seismic safety of urban tunnels have hitherto been limited to those for increasing the flexibility of tunnel structures by applying flexible joints and segments. However, since such techniques are insufficient for ensuring seismic safety of underground lifelines in urban areas when strong earthquakes occur, there has been a demand for developing a new, highly reliable technique, especially for protecting tunnel sections where seismic strain is concentrated locally. Given this situation, an innovative joint research project between the Public Works Research Institute and private companies was commenced to develop a seismic isolation system to be applied to urban tunnels. This paper describes the tunnel sections where seismic isolation can be applied effectively, seismic isolation materials developed by the joint research, and validation experiments conducted to confirm the feasibility of the methods for applying these materials.

INTRODUCTION

Several researchers have been investigating the application of a seismic isolation system to underground structures since around 1988, and the effectiveness of seismic isolation has been confirmed by numerical analyses and laboratory experiments[1)-5)]. As shown in Fig. 1, the fundamental principle of the seismic isolation system for underground structures is to cut off the transmission of ground strain by isolating a tunnel body from the peripheral soil by forming a thin, soft layer around the tunnel.

In the case of axial or bending deformation of a tunnel that occurs in the longitudinal direction due to earthquakes, tunnel sectional forces can be effectively reduced when a seismic isolation

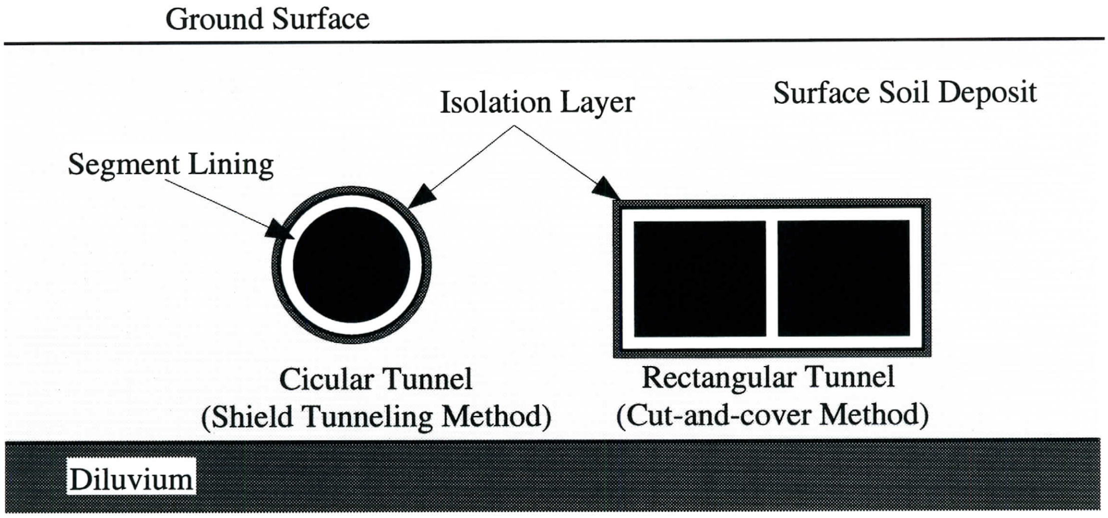


Fig.1 Schematic disgram to demonstrate the seismic isolation system for urban tunnels

layer is applied to a tunnel section where ground strain is concentrated locally. This is not only because the ground strain transmission to the tunnel body is cut off, but because the tunnel strain in the isolated section is dispersed.

In a similar vein, when cross-sectional deformation of a tunnel occurs, the results of numerical analyses have shown that the seismic isolation system helps to reduce the sectional forces concentrated at the corner portions in a tunnel with a rectangular cross-section constructed by the cut-and-cover method, thus contributing greatly to the reduction of sectional forces at the upper and lower slabs and side walls of such a tunnel[6),7)].

Meanwhile, earthquake response analyses were conducted to examine the effectiveness of the application of seismic isolation system to a subway tunnel that was severely damaged by the Hyogoken-nanbu earthquake of 1995[6)]. In the case of tunnels with a circular cross-section such as shield-driven tunnels, however, there was a report that the application of seismic isolation was not so effective in reducing sectional forces during cross-sectional deformation due to earthquakes[8)].

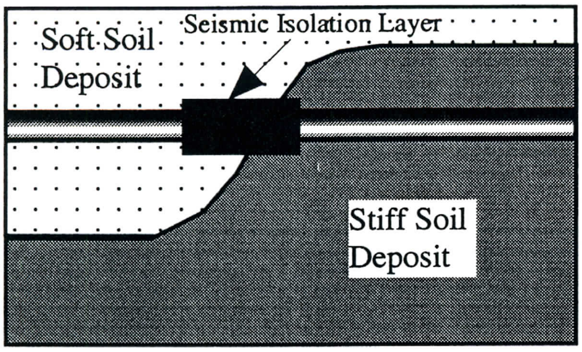
Since there has been no systematic research on the seismic isolation system, with which a thin seismic isolation layer is formed covering a tunnel body, studies on this system as described above, development of materials for the seismic isolation layer, and validation tests for developing construction methods have been conducted separately by various institutions[8),9)]. Thus, a comprehensive three-year project for clarifying the seismic isolation mechanism, and for developing seismic isolation materials, application methods, and seismic design, was started in July 1995 as a joint research project between the Public Works Research Institute of the Ministry of Construction and 17 private-sector companies in Japan. This paper will examine the results of this joint research, focusing on the tunnel sections where the application of the seismic isolation is effective, as well as the development of seismic isolation materials and validation tests conducted for confirming the feasibility of application methods.

TUNNEL SECTIONS AND THE MECHANISM OF THE SEISMIC ISOLATION SYSTEM

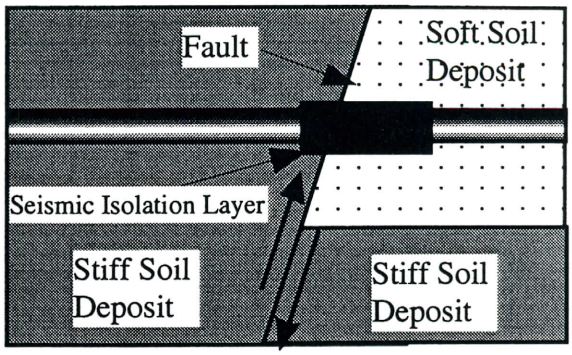
The tunnel sections where seismic isolation is considered to be effective are (1) sections where geological conditions change abruptly and (2) junctions with different structures, such as vertical shafts, and sections with sharp structural variations. The sections where geological conditions change abruptly can be further classified into several categories: (a) boundaries between soft and stiff soil deposits; (b) sections near fault or fracture zones; (c) sections where the thickness of subsurface layers changes abruptly due to irregular boundaries with bedrock; and (d) sections where the predominant frequency of the surface ground changes abruptly due to artificial filling and construction of structures as shown in Fig. 2.

Fig. 3 illustrates the distribution of longitudinal ground strain of the surface ground composed of two types of soil deposits with different soil impedances bounded by a vertical geological boundary, which is from a study on the boundary between soft and stiff soil deposits where abrupt change in geological conditions is commonly observed. As shown in Fig. 3, the more conspicuous the impedance contrast of the left and right soil deposits becomes, the more intense the local concentration of longitudinal strain on the soil boundary becomes. This means, in turn, that tunnels constructed in such places become subject to excessive ground strain transmitted through the tunnel structure during earthquakes. Fig. 4 is a schematic diagram that illustrates the effect of the seismic isolation applied to a section where the ground strain is concentrated. As shown in the figure, the seismic isolation layer can isolate the tunnel section from the surrounding ground, where ground strain is concentrated over a certain area. Idealistically, the values of the strain within the isolated section, which are determined by the tunnel stiffness and the displacement responses of the ground on both left and right sides of the isolated section, should be constant. In actuality, however, peak values of tunnel strain appear at the sections where strain is concentrated because small-scale ground strain is transmitted from the surrounding ground to the tunnel due to the slight stiffness of the seismic isolation layer. Thus, the tunnel sections where seismic isolation is applied and the shear modulus of seismic isolation materials should be determined according to the tunnel strain distribution.

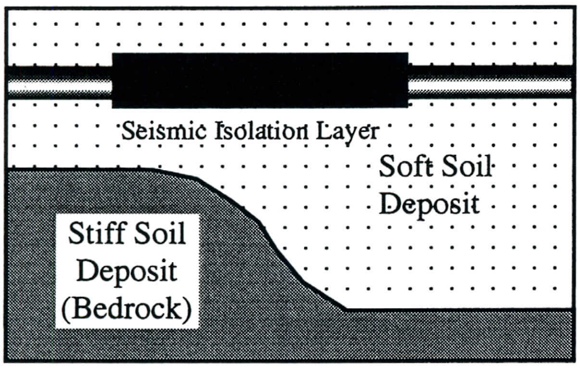
In addition to the concentration of ground strain, a tunnel section located close to a shaft which is connected to the tunnel becomes subject to the concentration of tunnel strain during earthquakes, since such a junction is a structural boundary between the tunnel and the shaft whose natural vibration characteristics are different from those of the tunnel body. Accordingly, such a section requires a seismic isolation layer for isolating the tunnel from both the peripheral soil and the shaft body. Fig. 5 is a schematic diagram showing the effect of seismic isolation applied to a tunnel-shaft junction of a shield-driven tunnel, along with a case in which a flexible segment is installed at a junction for comparison. Although the flexible segment provides high displacement absorption as shown in the figure, the distance in which the tunnel sectional force reduction takes effect is short in the case of non-isolation, since tunnel strain cannot be concentrated to the flexible segment due to the shear resistance from the peripheral soil around the segment neighboring the flexible segment. On the other hand, with the seismic isolation system, the sectional forces can be reduced effectively in accordance with the areas covered by the seismic isolation layer, which is more reliable than the flexible segment because there is no mechanical uncertainty.



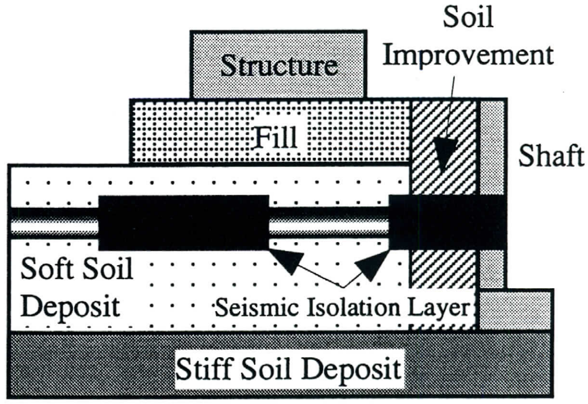
(a) Boundary between soft anf stiff soil deposits formed in a sedimentary process



(b) Section near fault or fracture zones



(c) Section where the thickness of sub-surface layers changes abruptly due to irregular boundaries with bedrock



(d) Junction with a vertical shaft
(e) Transition of natural periods of sub-surface ground due to filling and construction of a structure

Fig.2 Sections where the application of seismic isolation is effective

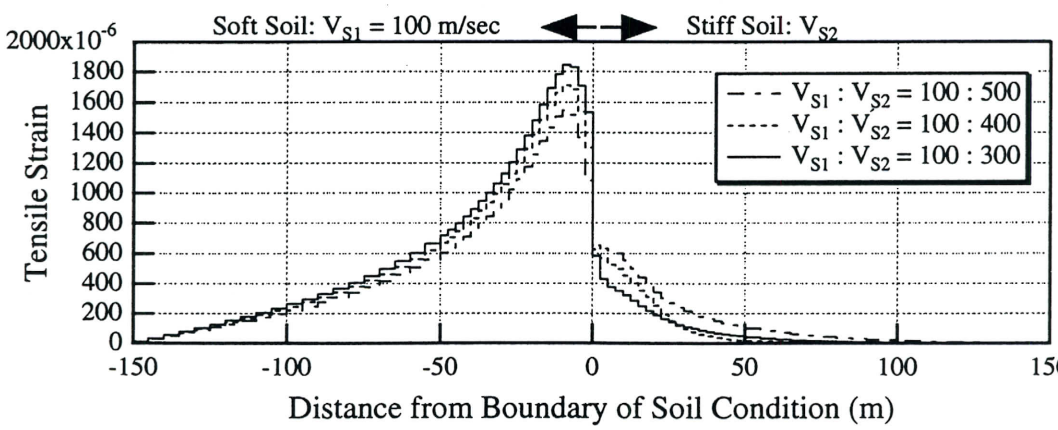


Fig.3 Longitudinal ground strain of the surface ground composed of two types of soil deposits with different soil impedances bounded by a vertical geological boundary

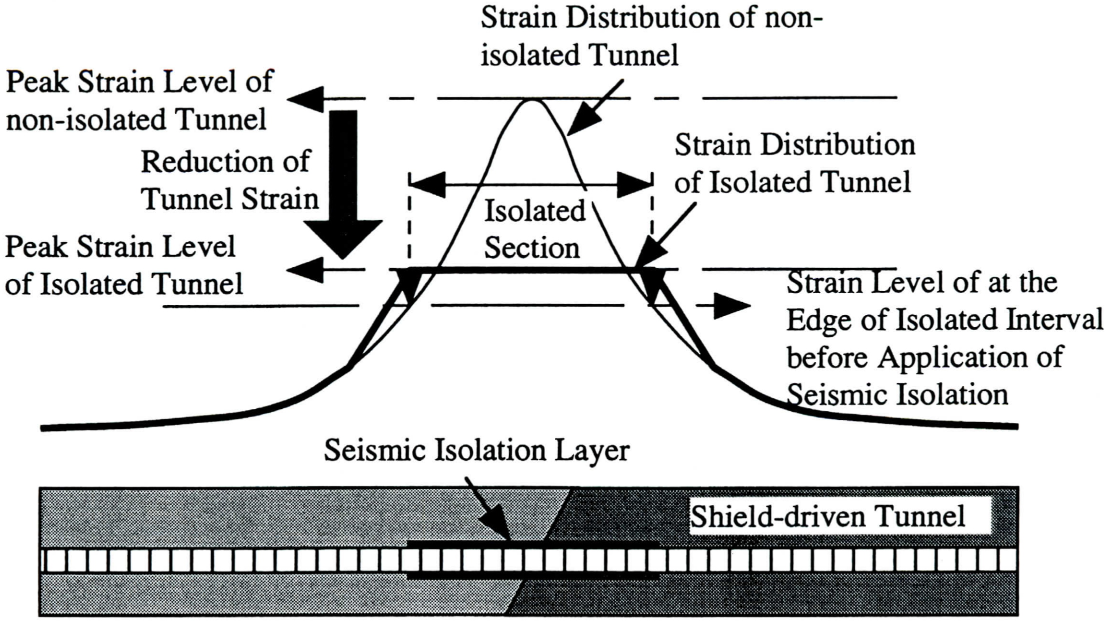


Fig.4 Schematic diagram to demonstrate the application of seismic isolation to the boundary between soft and striff soil deposits

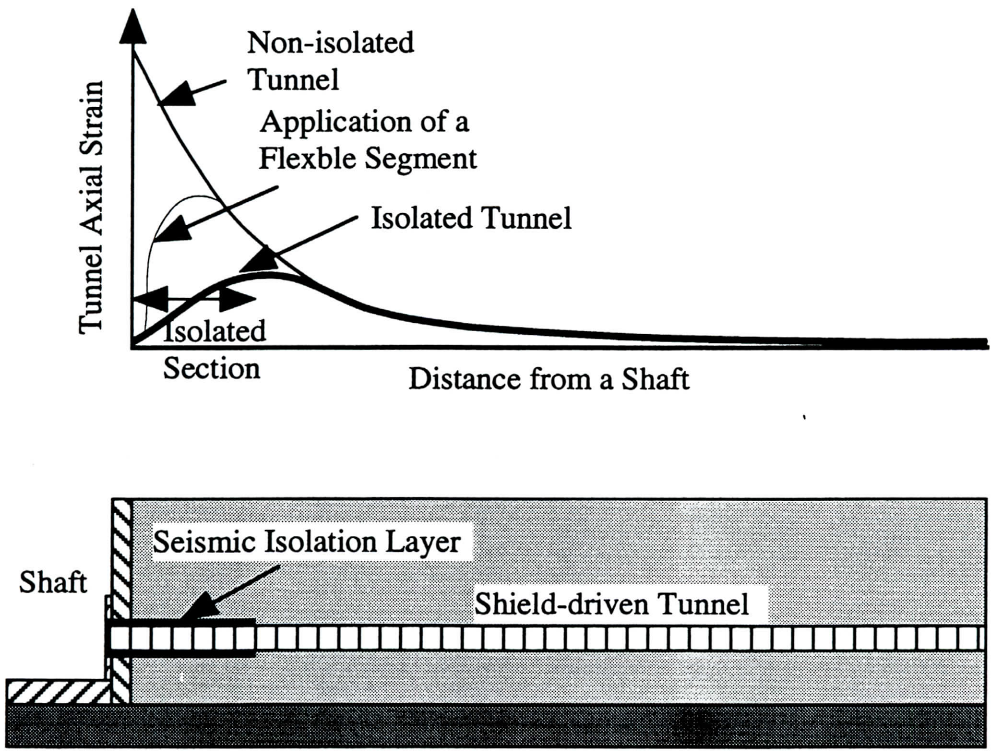


Fig.5 Schematic diagram to demonstrate the application of sesimic isolation to a junction with a shaft

DEVELOPMENT OF SEISMIC ISOLATION MATERIALS

A total of five different seismic isolation materials were developed, three for shield-driven tunnels and two for tunnels by the cut-and-cover method. They provide highly effective seismic isolation, meet the criteria of properties that are considered indispensable in the ordinary static design of these tunnels (such as watertightness and ground settlement prevention), and have the performance that is required for constructing these tunnels.

Despite slight differences due to the type of tunnel (shield-driven tunnels and tunnels constructed by the cut-and-cover method), the main properties required for seismic isolation materials can be summarized as follows[10]:

(1) Low shear modulus
(2) High shear deformability
(3) High durability and long-term stability
(4) Watertightness
(5) Extremely small volumetric changes at injection, vulcanization, and thereafter
(6) Transportability by pumping in a liquid state without any material separation
(7) High filling-up performance
(8) No dilution by groundwater
(9) No contaminants

Seismic Isolation Materials for shield-driven tunnels

A seismic isolation layer for shield-driven tunnels is formed by injecting and filling up an isolation material to the tail void generated during shield driving work. The properties (4) through (9) listed above are also required of the materials for filling the tail void in ordinary shield driving. The seismic isolation materials developed in the joint research are outlined below:

<u>Asphalt-based Material (Toa Doro Kogyo K. K.)</u>

The base material of the asphalt-based material is a mixture of asphalt emulsion and high-early-strength portland cement. When mixed with a high water-absorbing polymer, it gelates in 10 to 30 seconds, gradually hardens due to the hydration of the cement, then finally becomes a solid mass about one month after injection.

<u>Urethane-based Material (Asahi Denka Kogyo K.K.)</u>

The base material of the urethane-based material is isocyanate. When a mixture of fly ash and polyor is added as a hardener and mixed, it starts to vulcanize in several hours, and becomes urethane elastomer with low elastic modulus and high deformability one day after curing. The addition of a special polyor when mixing with the hardener can increase its viscosity up to 100 poise in one minute after injection, which stabilizes the excavated soil face of the tail void.

<u>Silicone-based Material (Shin-Etsu Chemical Co., Ltd.)</u>

The base material of the silicone-based material is composed mainly of silicone oil and fly ash. When a hardener is mixed in, it vulcanizes in about three hours after injection, and becomes a rubber-like solid in one day. Reacting to silica contained in the base material, polyether contained in the hardener increases the viscosity up to 200 poise in about 10 seconds, and stabilizes the excavated soil face of the tail void.

Seismic Isolation Materials for Tunnels by the Cut-and-Cover Method

In the case of tunnels constructed by the cut-and-cover method, seismic isolation materials are not injected into the earth, unlike the case with shield-driven tunnels. Since the space is narrow, where the seismic isolation system work is conducted, the materials must be well contrived. The seismic isolation materials developed in the joint research are outlined below:

Liquid Rubber (Tokai Rubber Industries, Ltd.)

The base material of the liquid rubber is a mixture of polybutadiene-type liquid rubber and asphalt. When polyisocyanate is mixed in as a hardener, this liquid rubber becomes a rubber-like solid in one day. Even when the job site is not spacious enough, such as when applied to the side walls of tunnels constructed by the cut-and-cover method, this uniform rubber-like solid can be formed by using molds.

Precast Rubber Panel (Sumitomo Rubber Industries, Ltd.)

The precast rubber panel is made by solidifying rubber tips made of shredded tires using urethane prepolymer resin. Coated by urethane resin, the panel surface is waterproof. This is a precast product produced in a factory, that is shaped into panels of a certain size to facilitate handling. Adhered to tunnel walls at job sites, the panels form a seismic isolation layer.

Hollow Cylindrical Cyclic Shear Tests

The seismic isolation layer is formed between a structure and its peripheral soil at a depth anywhere from a few meters to tens of meters below the ground level. In addition to a static constrained pressure generated underground, the layer becomes subject to compulsory shear deformation during earthquakes in both the axial and cross-sectional directions of the tunnel. Therefore, dynamic properties of the seismic isolation materials should be measured by giving cyclic shear loading under the same constrained conditions as underground. In consideration of the frequency dependency in the material properties, the loading frequency should be similar to the predominant frequency of the surface soil deposit. Thus, it was decided to measure the dynamic properties of seismic isolation materials by conducting hollow cylindrical dynamic shear tests (Photo 1), which are commonly conducted for testing dynamic shear properties of soil materials.

The frequency of cyclic loading used in the tests is 1 Hz which corresponds to the average frequency of the surface deposits. Starting with a small level, the shear amplitude was increased gradually until it reached 20% in the final stage. The rotational displacement measurement method using a laser displacement gauge was adopted, since the cyclic shearing was to be measured with such large shear amplitudes and at 1 Hz. To verify the dependency of the constrained pressure of material properties, similar cyclic loading tests were conducted using three different constrained pressures, i.e., 0.5, 1.5, and 3.5 kgf/cm^2. Using 11 sine waves, loading was applied cyclically to the respective shear strain amplitudes, and the shear modulus and the damping factor were calculated based on the hysteresis loop of the stress-strain relationship at the 10th cycle and thereafter. The dynamic properties of the silicone-based material, which is one of the most commonly used materials, are described below:

Figs. 6 and 7 show the strain-dependent curves of shear modulus G and damping factor h, respectively. These figures indicate that the material provides a constant property regardless of the depth where tunnels are constructed, since neither G nor h presents any constrained pressure dependency, despite the fact that the constrained pressure given in the tests had a considerably large range of 0.5 to 3.5 kgf/cm^2. Since the values of shear modulus G of the material are

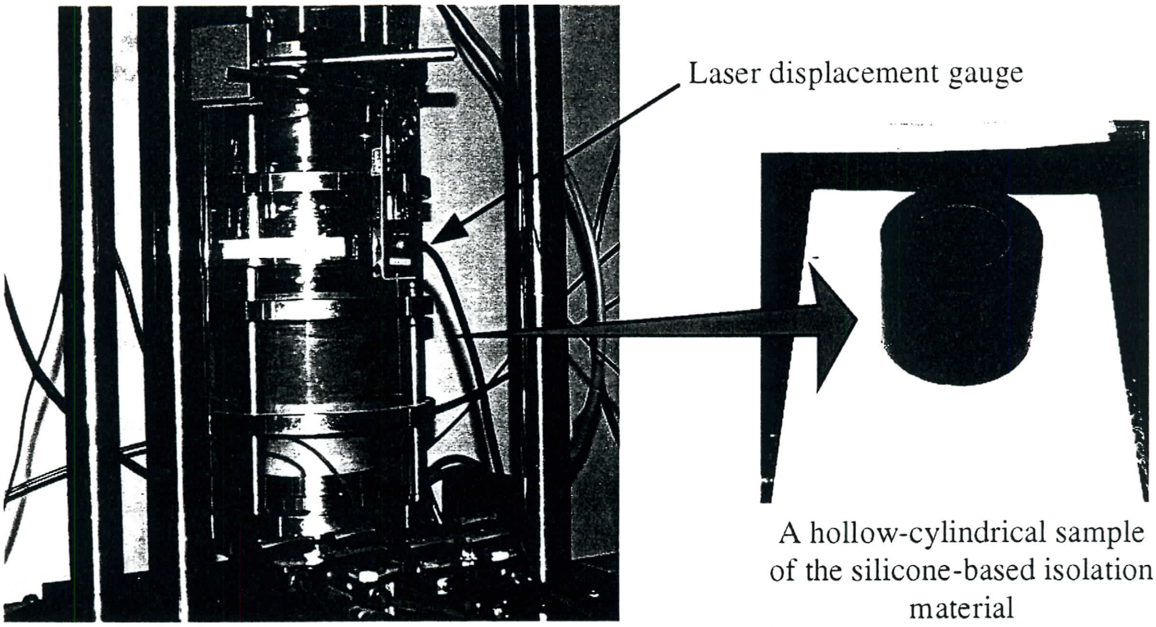


Photo.1 Dynamic shear test using a hollow-cylindrical cyclic shear apparatus

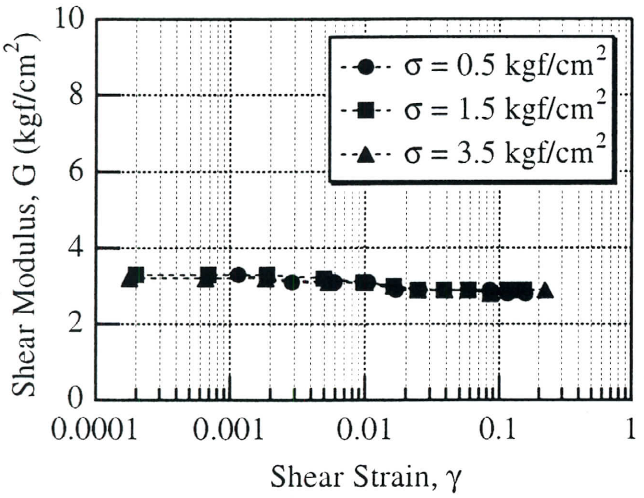


Fig.6 Strain-dependent characteristics of shear modulus for the silicone-based material

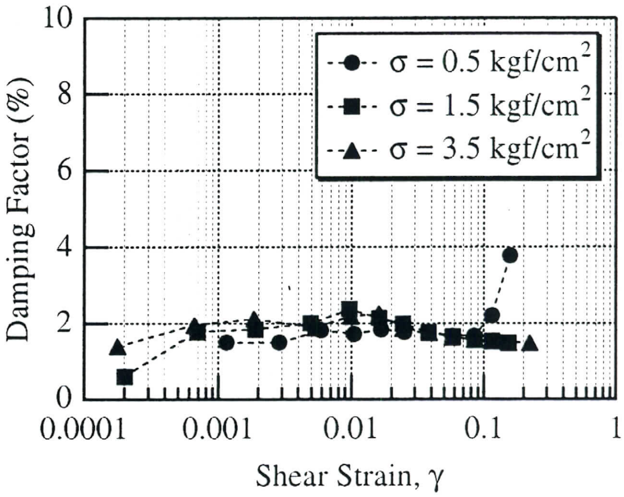


Fig.7 Strain-dependent characteristics of damping factor for the silicone-based material

constantly around 3 kgf/cm^2 without any strain amplitude dependency (unlike the case with soil materials), G measured during micro strain may be used when the seismic isolation effect is evaluated in the phase of design.

In addition, the values of damping factor h were around 2 % without any strain dependency. When the seismic isolation system is applied to underground structures, no hysteresis damping of the material is likely to occur. Thus, the seismic isolation materials developed in the joint research were proven stable even during the cyclic shear loading with large amplitudes.

DEVELOPMENT OF SEISMIC ISOLATION METHODS[11)]

In the case of shield-driven tunnels, a seismic isolation layer should be formed securely around a tunnel by injecting and filling a liquid isolation material into the tail void which is generated during shield driving work, in the same manner as with the filling work conducted during shield driving. It is thus necessary to produce prototypes of the equipment for the mixing and pumping systems for each seismic isolation material to conduct experiments for confirming the feasibility of the respective methods. In the joint research, two feasibility tests were conducted to verify the methods for applying the seismic isolation materials, i. e., injection into a model ground chamber and a trial injection at actual tunneling sites.

Fig. 8 shows the time-dependent variations of the viscosity of the silicone-based material after injection. As shown in the figure, this material attains high viscosity immediately after injection, fills up the tail void, and sustains the earth pressure. If an additional injection is applied, this material becomes thixotropic and provides a plastic flow that expedites the filling. As shown in Photo 2, a prototype injection facility was produced, and injection tests using a model soil chamber were conducted to verify the feasibility and practicality of this experimental facility. The chamber used for the injection tests is also used for testing the backfilling materials for shield tunneling work; thus, the test results showed that silicone-based material injection was as practical as using backfilling materials. In addition, a similar test was also conducted for the urethane-based material using the same chamber.

Photo 3 shows a trial injection of the silicone-based material into the tail void at an actual shield tunneling site. The material was injected into the tail void of actual earth with groundwater, and sampling cores from grout holes that had been drilled in segment pieces beforehand confirmed that a seismic isolation layer with the target properties and thickness was formed. The same trial injection was conducted for the asphalt-based material, which was also confirmed to be highly feasible.

In the case of the liquid rubber applied to tunnels by the cut-and-cover method, it is necessary to confirm its mixing and vulcanization characteristics. This material was placed between a concrete sheet pile and a wooden form using a prototype injection facility. As a result, it was confirmed that a seismic isolation layer with a uniform property was formed on the concrete wall as shown in Photo 4. Another prototype was produced to test the precast rubber panel, and it was confirmed that a seismic isolation layer was formed satisfactorily as shown in Photo 5, as the panel adhered to a concrete sheet pile with sufficient strength.

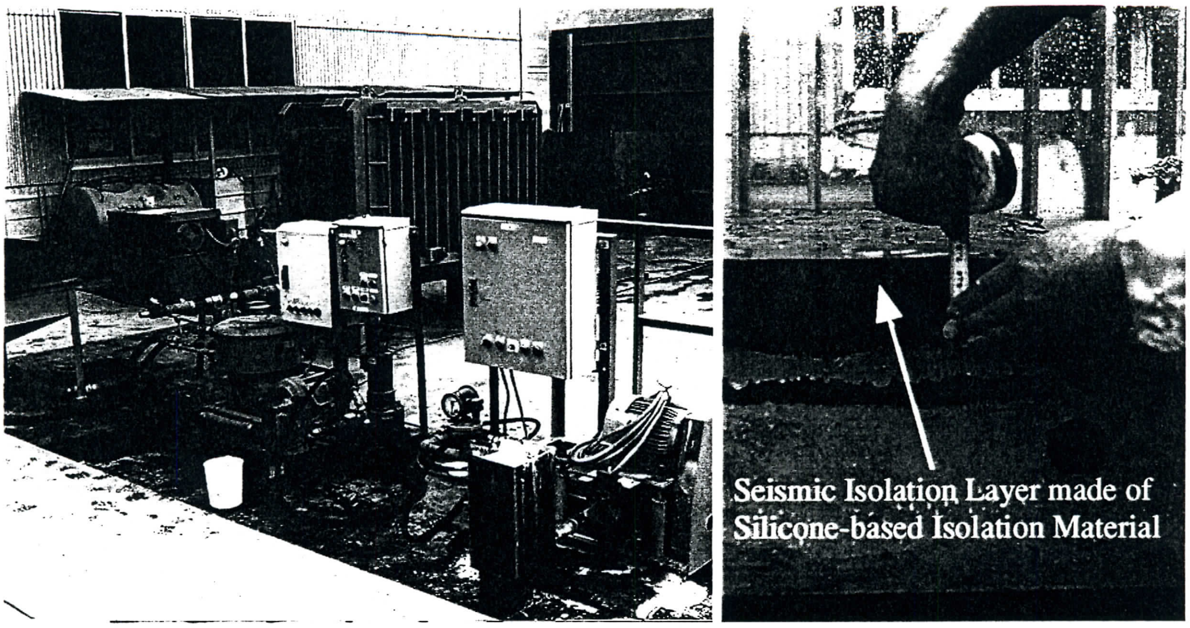


Photo.2 A Protopype injection facility and injection test using a model soil chamber (left) and the formation of an isolation layer after the injection test (right)

Photo.3 Trial Injection of the silicone-based material into a tail void at an actual shield tunneling site

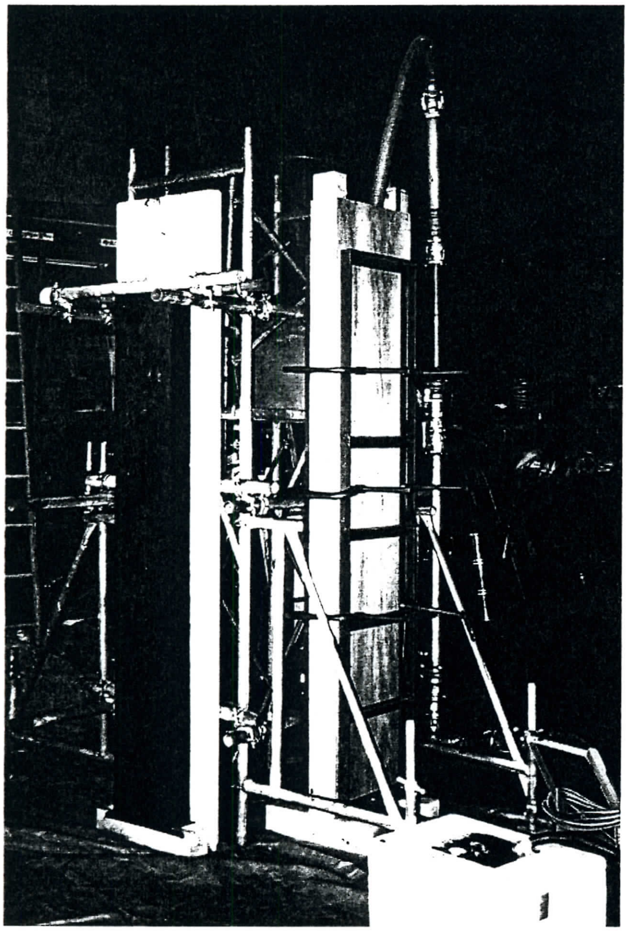


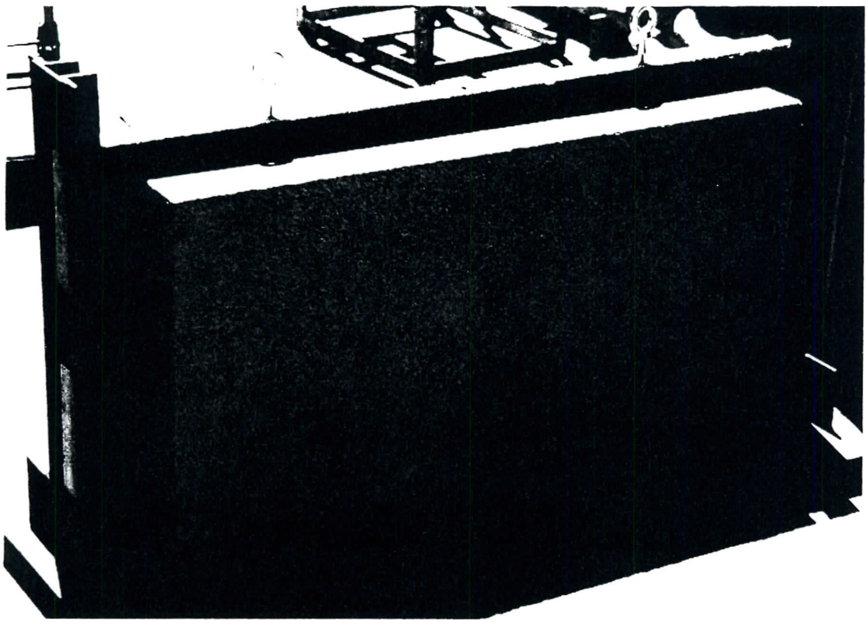
Photo.4 Injection test for the liquid rubber

A black panel stuck to a concrete sheet panel in the left hand side is the seismic isolation layer made of the liquid rubber.

The liquid rubber is being injected into a form in the right hand side.

Photo.5 Tests for the precast rubber panel

The precast rubber panel is adhered to the concrete sheet panel covered by a rubber sheet for water-proofing.



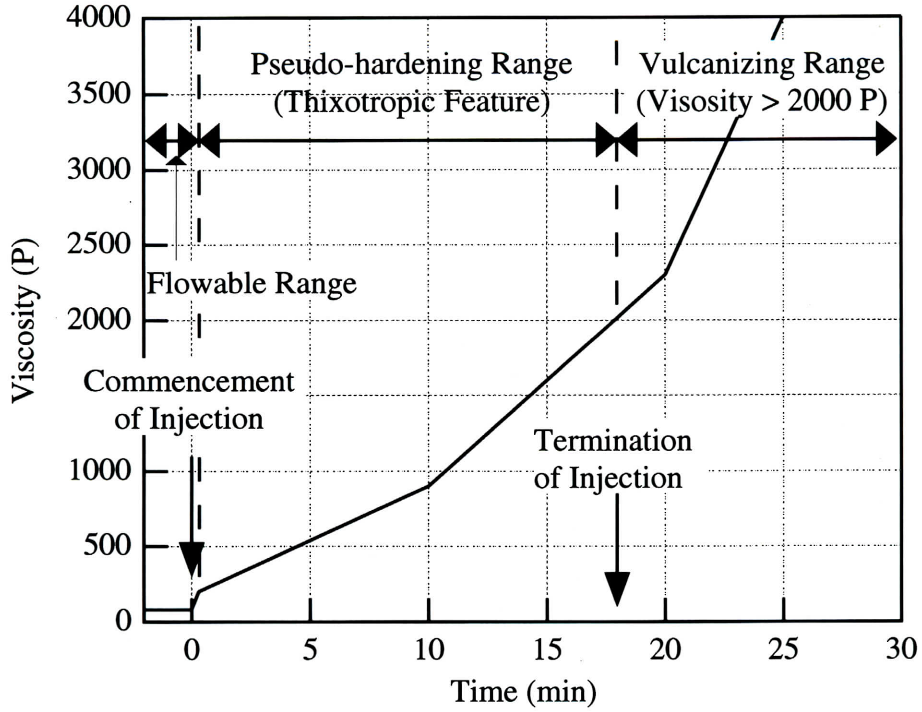


Fig.8 Representative time-dependent variations of the viscosity of the silicone-based material

CONCLUDING REMARKS

This paper has briefly described the seismic isolation system for underground structures focusing on the tunnel sections where the application of the seismic isolation takes effect, the development of seismic isolation materials, and validation experiments conducted for confirming the feasibility of the application methods. Five different seismic isolation materials applicable to shield-driven tunnels and tunnels by the cut-and-cover methods were developed, which have been proven promising for practical use as a result of material and validation tests. Now the authors intend to apply the developed technology to practical construction works to help prevent earthquake-related damage to lifelines.

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