RESEARCH AND DEVELOPMENT ON THE SEISMIC ISOLATION SYSTEM APPLIED TO URBAN TUNNELS
(PART-2: EFFECTS OF SEISMIC ISOLATION AND SEISMIC DESIGN)

Tsutomu TANAKA1) and Takeyasu SUZUKI2)

1) Director, Central Research and Development Department, Oriental Consultants Co., Ltd.
2) Manager, Earthquake Engineering Research Group,Technical Research and Development Institute, Kumagai Gumi Co., Ltd.

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 will describe the results of analyses and experiments conducted for validating the effectiveness of seismic isolation, as well as the development of design methods.

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 experiments1)-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

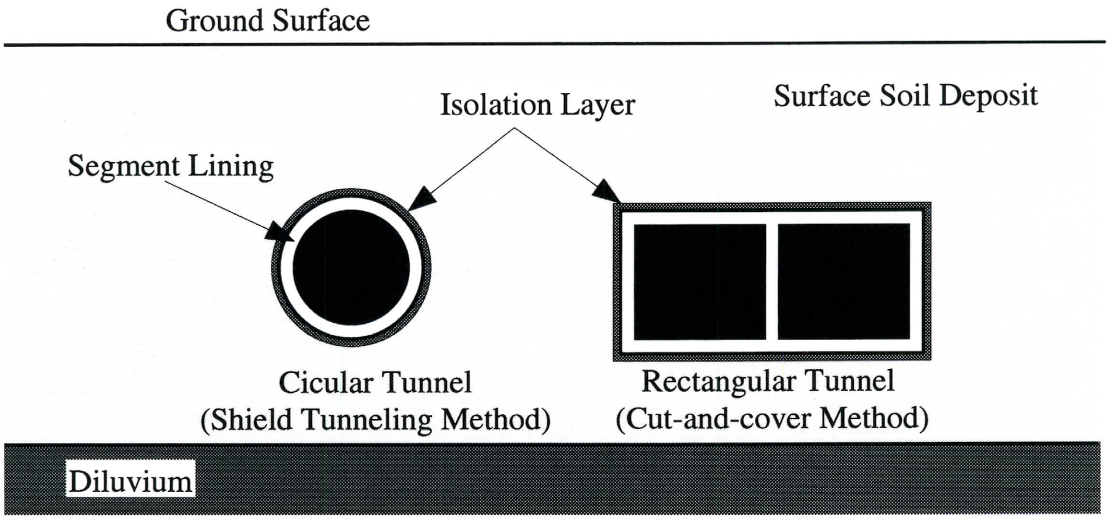


Fig.1 Schematic disgram to demonstrate the seismic isolation system for urban tunnels

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 tunnel6),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 19956). 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 earthquakes8).

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 institutions8),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 results obtained by analyses and experiments conducted for validating the effectiveness of seismic isolation, describe the results of a study on the development of design methods for seismic isolation tunnels, and presents the flow of the design methods.

EFFECTS OF SEISMIC ISOLATION

Longitudinal tunnel deformation during earthquakes

This chapter will examine the results of numerical analyses conducted for identifying the effect of reducing tunnel sectional forces by applying seismic isolation to shield-driven tunnels. The sectional forces acting on a tunnel in the longitudinal direction can be reduced by applying a seismic isolation layer to a section that becomes subject to the concentration of the maximum local ground strain. Such a layer is formed by injecting and filling the seismic isolation materials developed by the joint research, which are soft with a shear modulus of around 3 kgf/cm^2, into the tail void that is created during shield driving, and which is usually 5 to 10 cm thick. In this chapter, the reduction of sectional forces and the behavior of the isolated tunnel section are described in detail for seismic isolation that is applied to a shield-driven tunnel section located underneath a caisson-type quay.

The longitudinal tunnel section and the surrounding ground structure selected for the earthquake response analyses are illustrated at the top of Fig. 2. The numerical models used in the analyses are analogous to those proposed by Tamura et al.10), in which a mass-spring system and a beam-spring system are used for the ground and the tunnel, respectively. The ground model was made in consideration of the fundamental to the third shear vibration modes, using an extended quasi-two-dimensional model11) which is capable of handling the fundamental to the N-th shear vibration modes. The quay was considered a ground element with concrete properties. The soil was considered a linear material, whose stiffness had been reduced in reference to the initial value obtained beforehand by a one-dimensional equivalent linear analysis based on multiple reflection theory. Assuming that flexible segments absorb the displacement, extremely weak springs were used at a junction connecting the tunnel and shafts.

Two shield-driven tunnels composed of reinforced concrete segments of 5.4 m in outer diameter and 22.5 cm in thickness were used, one with and the other without seismic isolation. They are considered a non-linear element with stiffness that changes according to either tensile or compressive deformation.

The results of the analyses are summarized in (a) through (e) in Fig. 2. As shown in Fig. 2 (a), the maximum values of tunnel displacement are almost constant for the two tunnels regardless of seismic isolation; however, the gradient of the displacement distribution of the tunnel section located underneath the quay in the case of isolation is more gentle than in the case of non-isolation. The maximum axial force distributions in Fig. 2 (b) and (c) show that the seismic isolation layer reduced the axial force markedly to 1/10 for the compressive deformation and 1/5 for the tensile deformation. In addition, both the bending moment and the shear force decreased remarkably as shown in Fig. 2 (d) and (e). Thus, these analyses showed that the application of seismic isolation to a tunnel section where ground strain is concentrated is highly effective. Fig. 3 shows the time-dependent response of axial strain at a tunnel section where the tunnel sectional force hits the maximum for the two tunnels, one with and one without seismic isolation.

Seismic isolation at a junction with a shaft

When there is a junction with a shaft, seismic isolation takes effect when a seismic isolation layer is formed, covering a tunnel section measuring around 10 m from the shaft, for isolating the

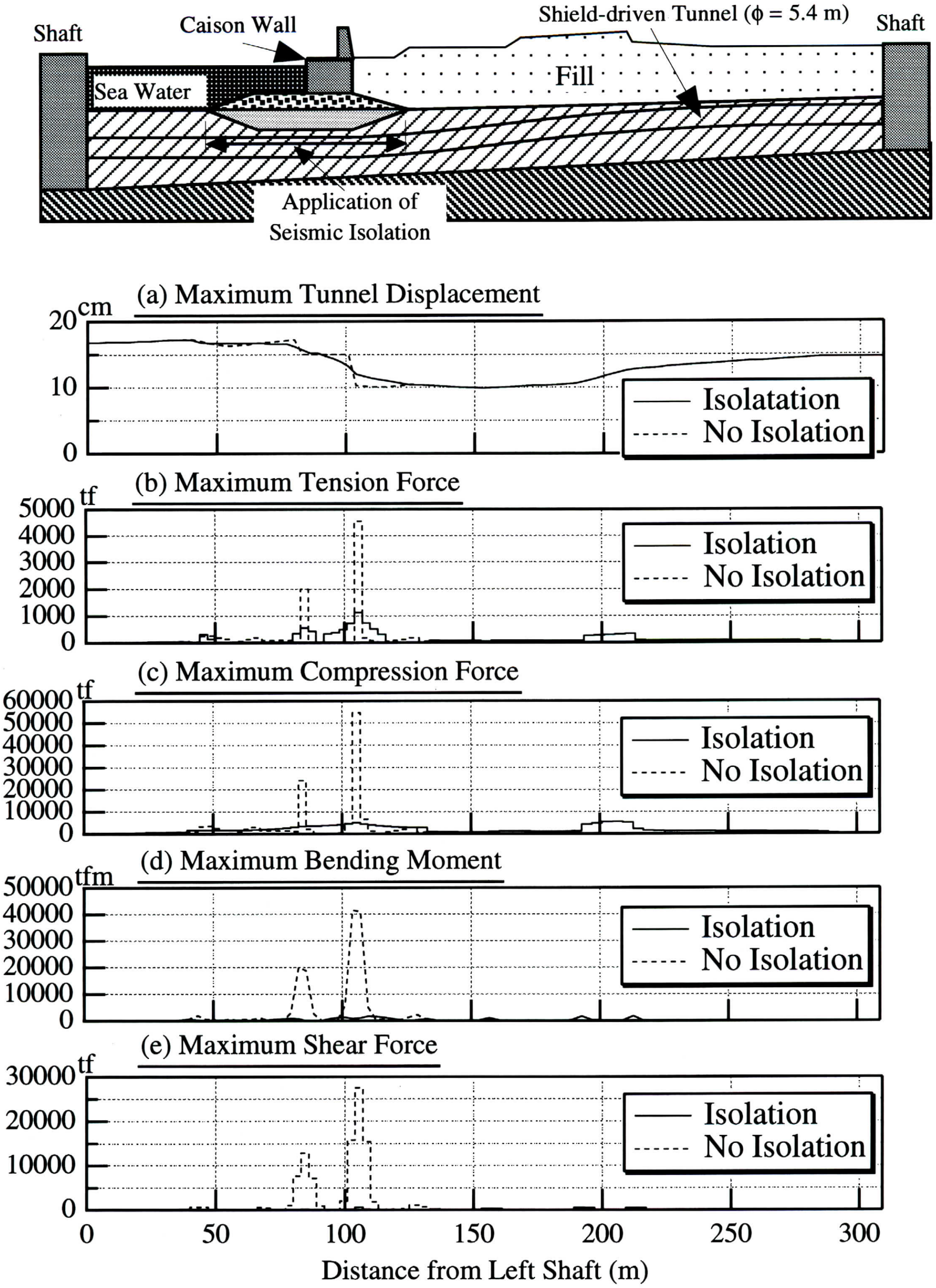


Fig.2 Comparison on tunnel displacement and internal forces between isolated and non-isolated tunnels, obtained by earthquake response analyses for a shield-driven tunnel underneath a caisson-type quay

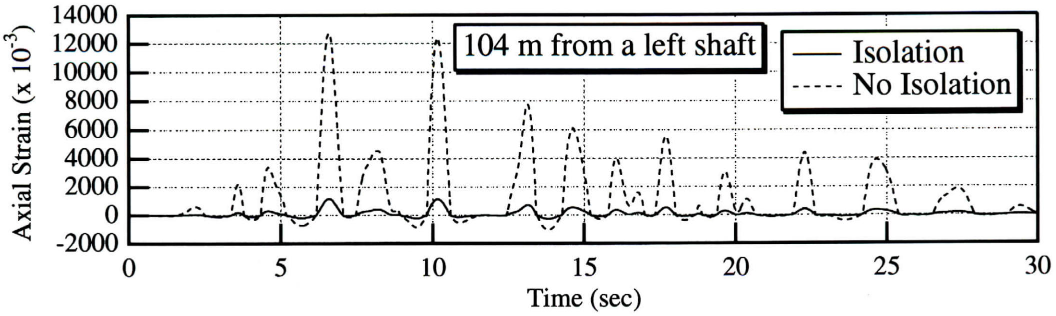


Fig.3 Comparison on time-dependent response of tunnel axial strain between non-isolated and isolated tunnels

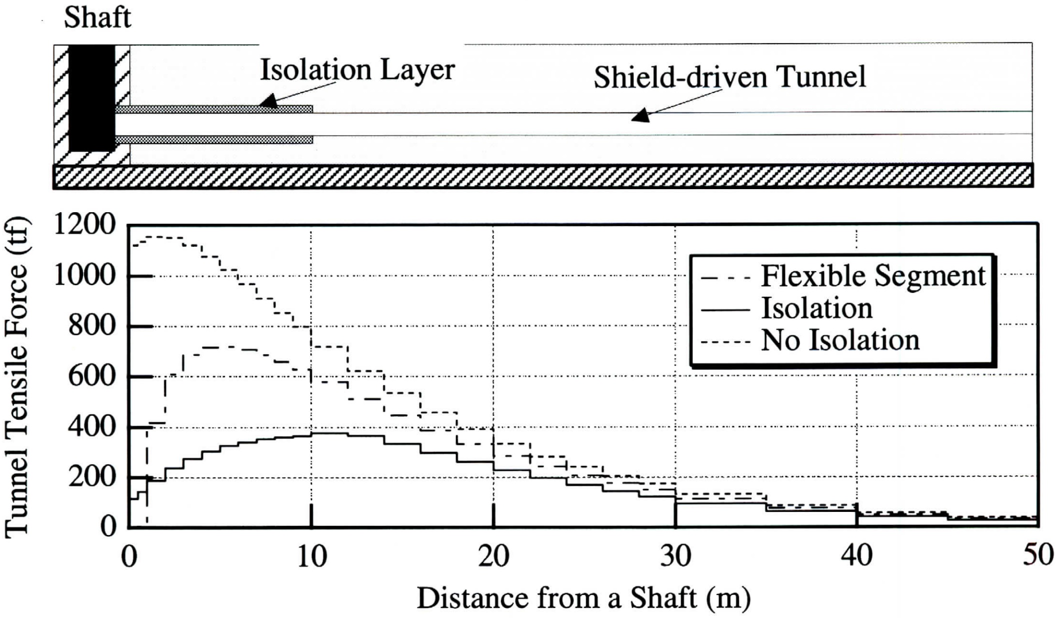


Fig.4 Comparison on tunnel axial forces at a junction with a shaft among three different cases

tunnel section from both its peripheral soil and the shaft body. Numerical analyses were conducted, using a shield-driven tunnel composed of reinforced concrete segments, 5.05 m in outer diameter and 25 cm in thickness, to examine the effect of the seismic isolation layer in reducing the sectional forces at such a junction. The model used was an axisymmetric finite element model (EASIT) developed in this joint research12),13). Statistically loading the entire model with inertial forces corresponding to 0.3 G of uniform horizontal earthquake acceleration, three cases were analyzed: (1) seismic isolation was applied to a ten-meter-long section around the shaft; (2) no seismic isolation was applied; (3) a flexible segment was installed on the first ring from the shaft. Fig. 4 compares the tunnel axial force distributions of these three cases. Despite the ability of the flexible segment to absorb large displacement, the effect of tunnel sectional force reduction reached only to the vicinity of the flexible segment. This is because the flexible segment failed to gather the tunnel strain completely due to the shear resistance of the peripheral soil acting on the outer surface of other tunnel segments nearby. When a seismic isolation layer was applied, however, the tunnel maximum axial force decreased up to 1/3, since the tunnel strain could be dispersed toward the shaft effectively. In addition, unlike the technique which uses a flexible segment, the seismic isolation system is highly reliable because there is no mechanical uncertainty.

Cross-sectional deformation of tunnels by the cut-and-cover method

In the case of cross-sectional deformation of a tunnel with a rectangular cross-section, which is usually constructed by the cut-and-cover method, great sectional forces are concentrated at the corner portions and the upper and lower edges of slabs and side walls during earthquakes. Therefore, model vibration tests were conducted to verify that such sectional forces can be reduced by covering the tunnel body with a seismic isolation layer that isolates the tunnel from its peripheral soil.

Photo 1 shows a view of installing model tunnels made of acrylic resins in a soil chamber. A tunnel model covered with a silicone rubber isolation layer and another tunnel model without any seismic isolation device were placed end to end on a vibration table, and oscillation was applied in a direction perpendicular to the tunnel axis. Then, the tunnel strain, as well as the shear stress and the normal stress acting on the outer surface of the tunnel bodies, were measured. Photo 2 shows a general view of this vibration test.

Fig. 5 illustrates one of the test results, comparing the bending moment distribution of tunnels with and without seismic isolation. As shown in the figure, the seismic isolation layer decreased the bending moment up to 1/3, which is concentrated to the corner portions of the tunnel. The shear stress acting on the outer surface of the tunnel was decreased to 1/10 or less by the seismic isolation layer, which was proven to be the most important factor reducing the tunnel sectional forces. Fig. 6 illustrates a shear stress distribution of the ground surrounding the tunnel obtained by the earthquake response analyses6). This is rather similar to the ground strain around a cavity without lining, since the seismic isolation layer that isolates the tunnel body from the peripheral soil changed the shear stress distribution around the tunnel greatly.

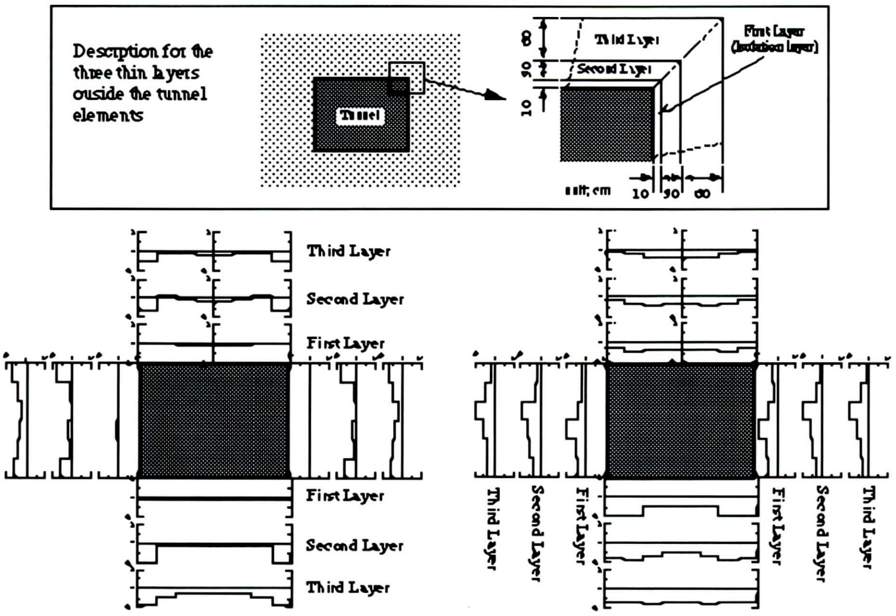


Fig.6 Shear stress distributions of thin layers aroud tunnel (left: isolated, right: non-isolated)6)

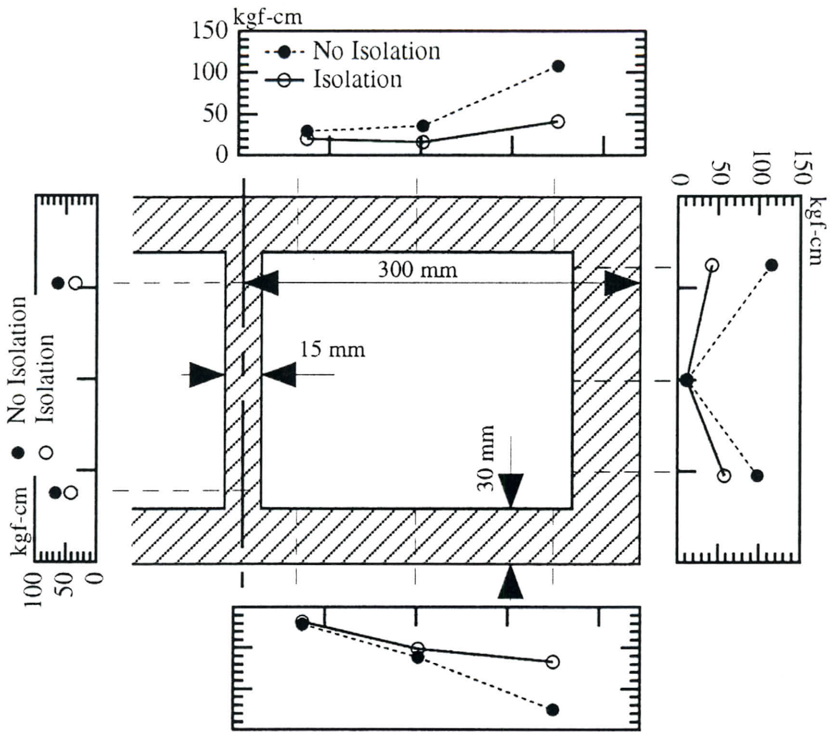


Fig.5 Maximum bending moment distribution obtained from model vibration tests

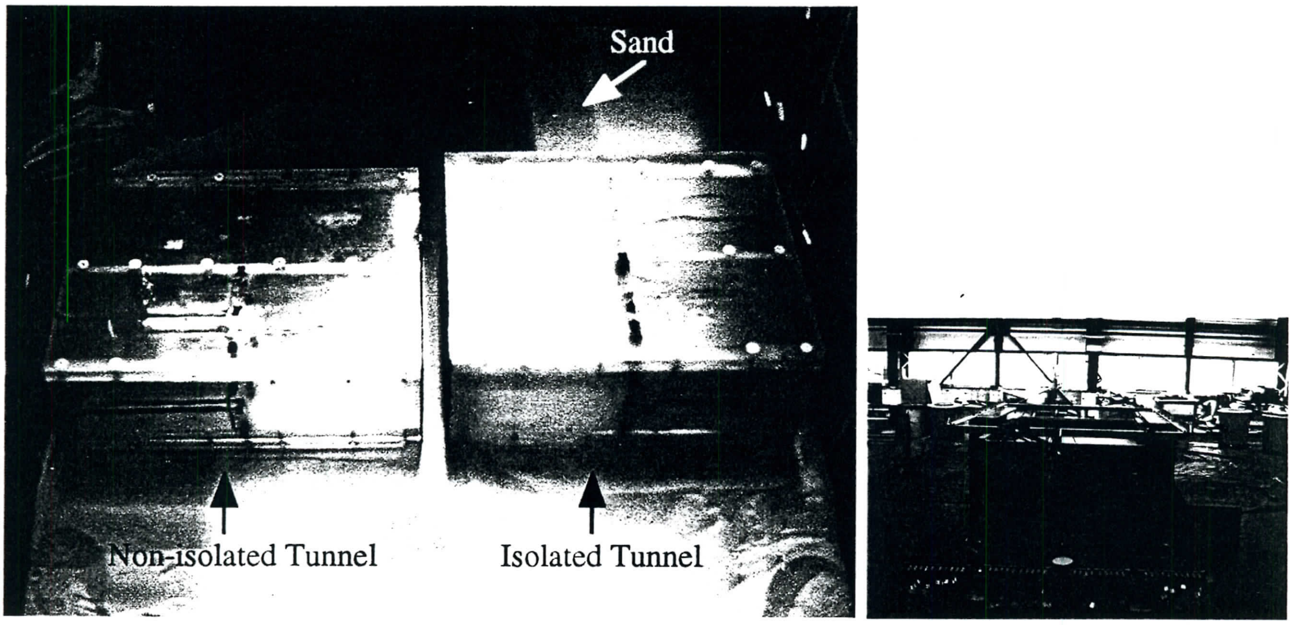


Photo.1 Arrangement of tunnel models (left) and a general view of the vibration test (right)

Factors affecting the seismic isolation effects

(a) Stiffness of a seismic isolation layer

As discussed in the previous chapter, seismic isolation takes effect when a seismic isolation layer is formed using materials with shear modulus of around 3 kgf/cm^2.

To identify the range of shear modulus, in which seismic isolation takes effect in the cross-sectional deformation during earthquakes, numerical analyses were conducted based on the seismic deformation method using a finite element model (will be described later). Fig. 8 shows a model of a large box culvert (illustrated in Fig. 7) and a subsurface ground. Fig. 9 summarizes the maximum sectional force ratios obtained at a side wall of two tunnels, one with and the other without seismic isolation, in which M/M_0 denotes the ratio of the bending moment; Q/Q_0, of the shear force; S/S_0, of the axial force; and the horizontal axis G_m/G_g, the shear modulus ratio of an isolation material to a subsurface deposit12). As shown in Fig. 9, the tunnel sectional forces decrease, the smaller the shear modulus of the materials becomes, and the effect of sectional force reduction is considerable when the ratio becomes 1/100.

Meanwhile, a shield-driven tunnel constructed in the subsurface ground composed of two soil deposits with different soil impedances bounded by a vertical geological boundary, was analyzed using an axisymmetric finite element model to identify the seismic isolation effect in the case of longitudinal deformation. Fig. 10 summarizes the results of the analysis in which the shear modulus of an isolation layer was used as a parameter13). As shown in the figure, the seismic isolation material reduced the tunnel sectional forces considerably, when the shear modulus was as low as 3 kgf/cm^2, which is equivalent to around 1/50 the peripheral ground.

When the shear modulus ratio of an isolation material is as low as 1/1000, the natural period of tunnel resonance vibration shifts to a low frequency range, and the sectional force distribution becomes different from that usually observed under static conditions. Thus, the shear modulus of an isolation material should be around 1/100 that of the peripheral ground.

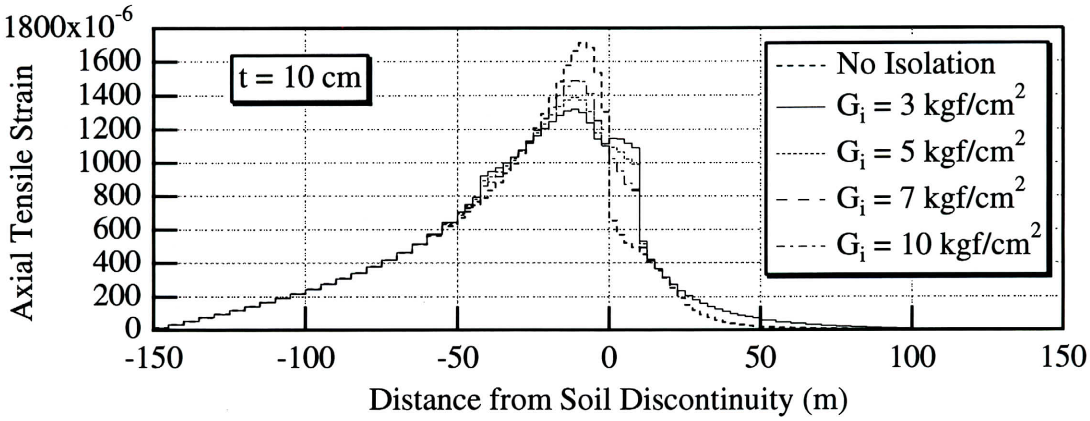


Fig.10 Effect of shear modulus of an isolation layer on the seismic isolation effec

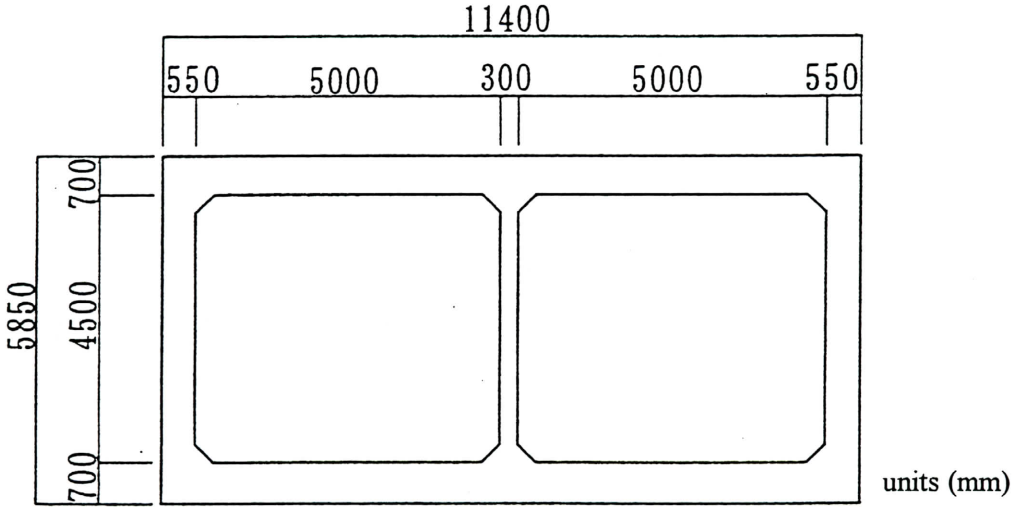


Fig. 7 Cross-section of a box culvert used for analyses

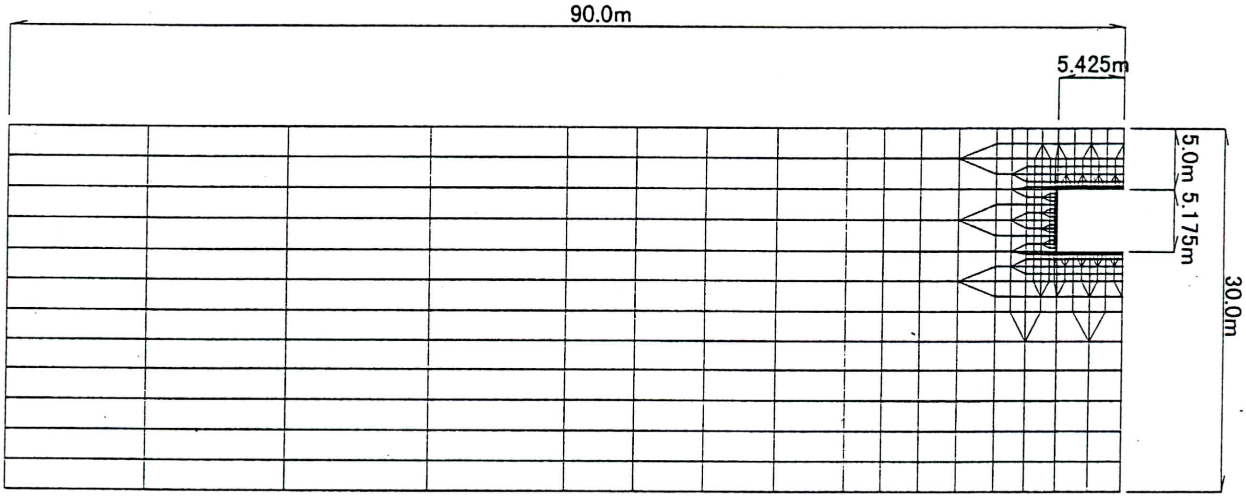


Fig. 8 Discretization of finite element mesh

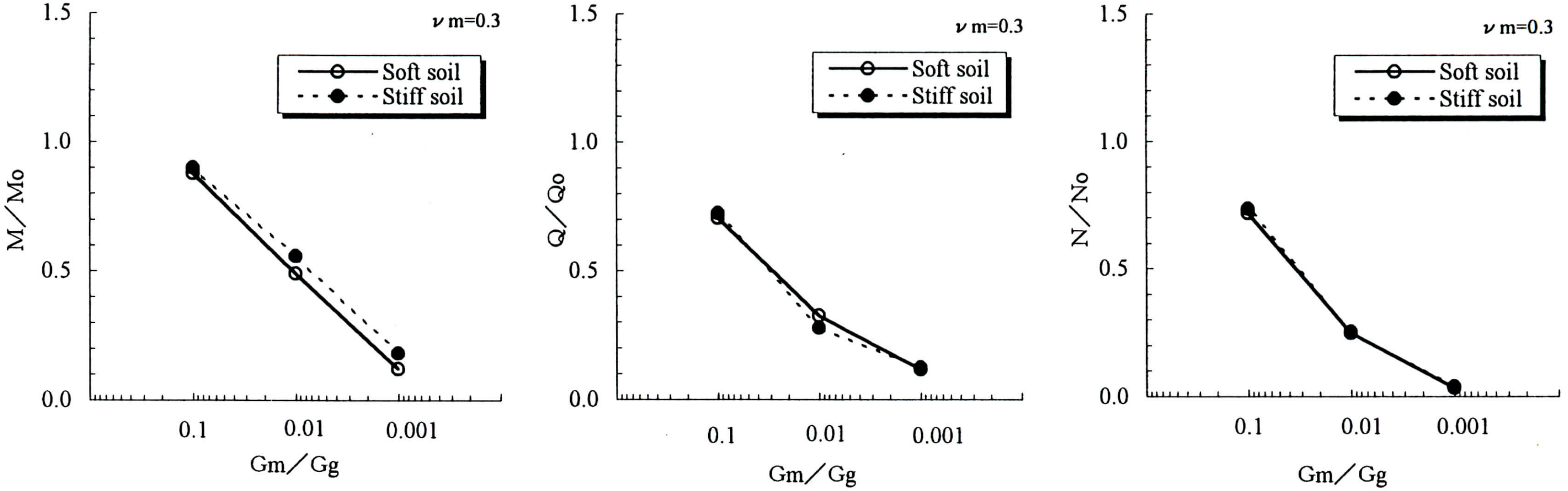


Fig. 9 The effect of the shear modulus ratio, Gm/Gg on sectional force reduction

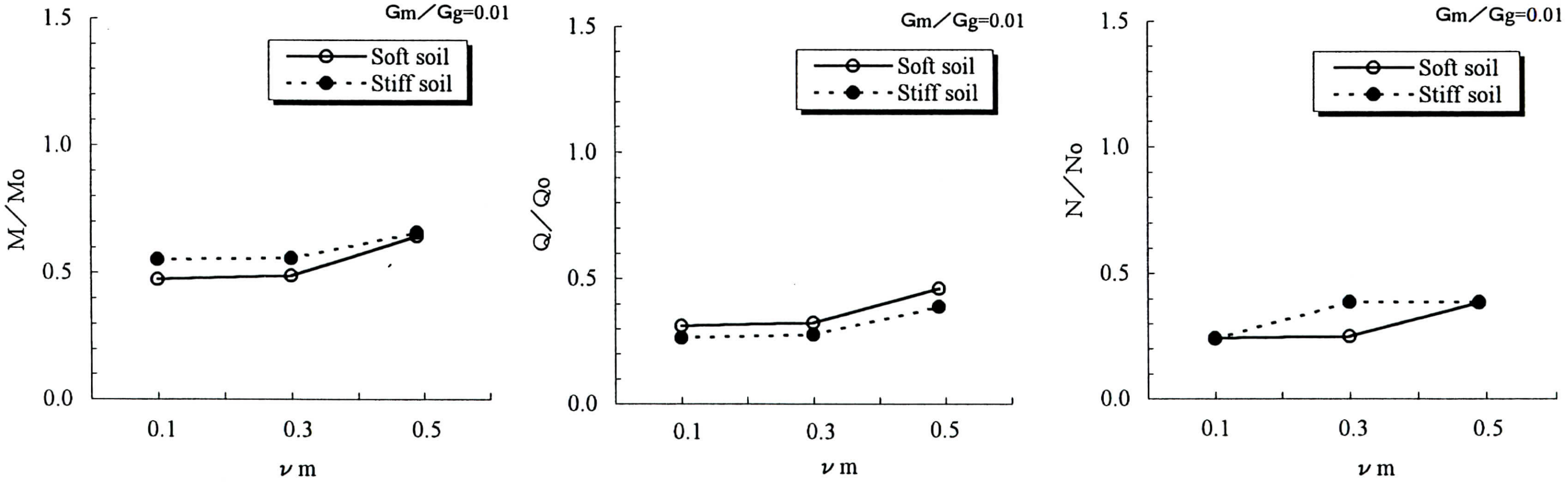
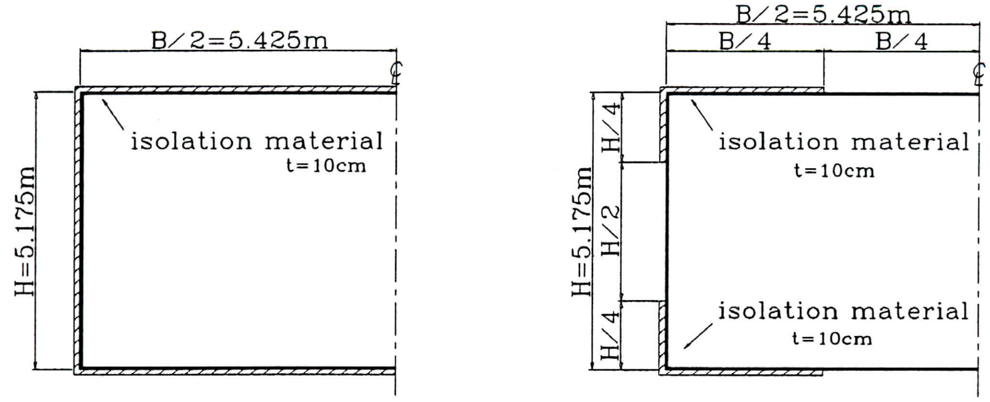
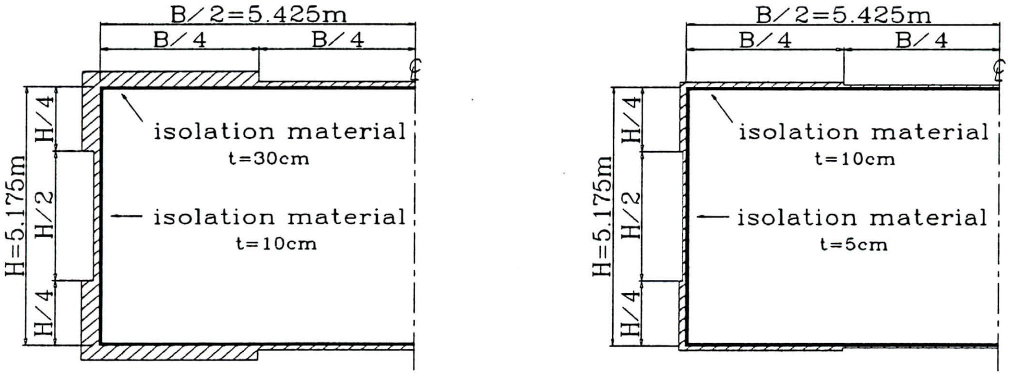


Fig.11 The effect of Poisson's ratio on sectional force reduction



(a) Fundamental Case

(b) Case-1



(c)Case-2

(d) Case-3

Fig. 12 Cases examined on the arrangement of seismic isolation layers

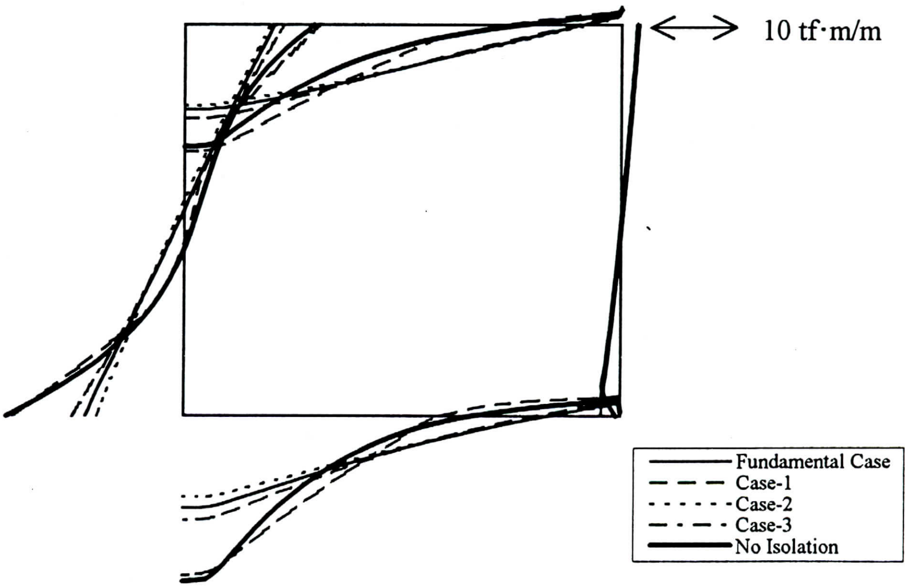


Fig. 13 Comparison of bending moment distributions among four cases

(2) Poisson's ratio of an isolation layer

Assuming that Poisson's ratio of an isolation layer may be affecting the effect of seismic isolation, since a seismic isolation layer is deformed greatly when the tunnel body is deformed in the cross-sectional direction, the authors conducted analyses based on the deformation method using the same model shown in Fig. 8, using Poisson's ratio as a parameter[12]. Fig. 11 shows the result of analyses on sectional forces at a side wall. It was confirmed, however, Poisson's ratio of an isolation layer did not affect the seismic isolation effect.

(3) Arrangement and thickness of an isolation layer

The effect of the arrangement and the thickness of an isolation layer on seismic isolation was examined, focusing on the cross-sectional deformation of a tunnel with a rectangular cross-section. Four cases of arrangement (Fig. 12) were analyzed using a tunnel model shown in Fig. 8[13]. The fundamental case is a tunnel covered by an isolation later with a thickness of 10 cm. Comparing the bending moment distributions of the four cases in Fig. 13, one can notice that the thickness of an isolation layer scarcely affects the tunnel sectional forces within the range of thickness used in the analyses, and that the seismic isolation layer does not manifest its maximum effect unless it is installed covering the entire outer surface of the tunnel.

The same effect in the case of longitudinal deformation of a shield-driven tunnel constructed in the subsurface ground described above was also analyzed using an axisymmetric finite element model. Fig. 14 illustrates a summary of the analyses in which the thickness of an isolation layer is used as a parameter[13]. The figure indicates that the effect of the thickness of an isolation layer on seismic isolation is negligible.

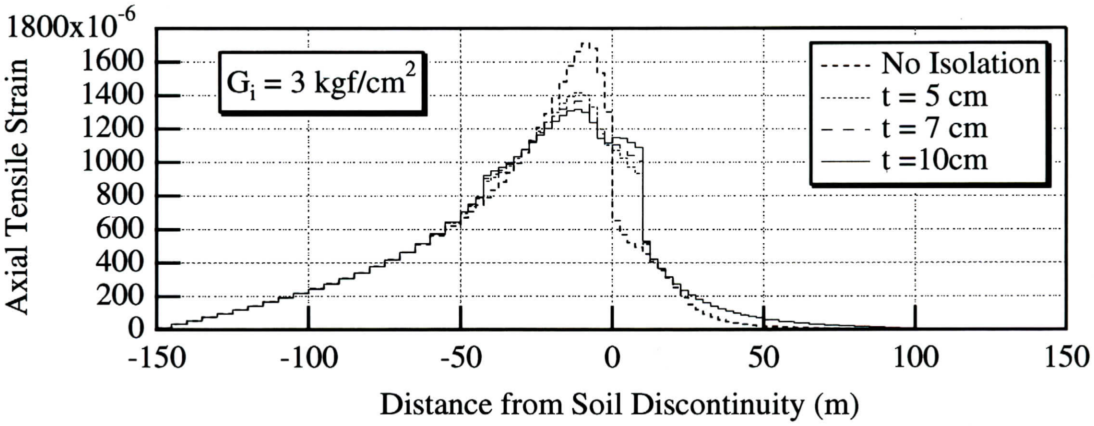


Fig.14 Effect of the thickness of an isolation layer on the seismic isolation effect

Procedures and the flow of design

(1) Static design

The static design for isolated tunnels is conducted in the same manner as that for non-isolated tunnels.

(2) Seismic design of the cross-sectional tunnel deformation

A finite element model as shown in Fig. 8 is used in the seismic design, so that the soil-structure interaction can be taken into consideration accurately. Although it is desired to conduct dynamic analysis using such a model for a precise output, a static method was used for simplifying the design methods on the assumption that the fundamental tunnel structure is designed without sufficient geological data.

Since the deformation of underground structures is governed by the ground deformation, it is necessary to generate the ground deformation, when a tunnel sectional force reaches its maximum value, by a static method. It is supposed that the ground vibration can be represented only by a fundamental mode of shear vibration, which is appropriate in many cases. In the case of a resonant vibration, the time that the ground displacement reaches its maximum value is coincident with the time that the ground acceleration reaches its maximum value. Therefore, the maximum vertical distribution of horizontal ground displacement can be obtained by loading the force of inertia, which corresponds to the acceleration distribution for fundamental shear vibration, to the finite element model. The force of inertia can be given by equation (1).

$$\begin{aligned} F(z) &= \frac{\gamma_t(z)}{g} A(z) \\ A(z) &= \phi(z)\,\beta\,S_A \end{aligned} \qquad (1)$$

where, z: depth
- $F(z)$: force of inertia at depth z
- $\gamma_t(z)$: weight per unit volume of soil at depth z
- g: gravitational acceleration
- $A(z)$: absolute acceleration at depth z
- $\phi(z)$: modal vector at depth z
- β: participation factor of the fundamental shear vibration mode
- S_A: absolute acceleration response vector at a natural period of fundamental mode of ground vibration

The authors named this method the "deformation method based on ground force of inertia."[12)]

(3) Seismic design on the longitudinal tunnel deformation

Seismic isolation in the longitudinal direction is conducted by applying a seismic isolation layer to a section where the tunnel strain is concentrated locally, such as a junction with a shaft and an area with abrupt transition of geological conditions. Thus, when conducting a seismic design, earthquake response analyses on the subsurface ground of a tunnel, using such numerical models as a mass-spring system and a 2-D finite element model, are conducted in the first place, followed by a determination of the section where seismic isolation should be applied based on the tunnel sectional forces obtained by the analyses.

As shown in Fig. 15, tunnel strain in an isolated region is dispersed and becomes uniform due to the redistribution of tunnel strain. The divergence of tunnel strain becomes remarkable, the smaller the shear modulus of an isolation layer becomes, and the larger the tunnel stiffness becomes. Such a tunnel strain redistribution is confirmed by static analyses using an axisymmetric finite element model, a simplified three-dimensional finite element model, or a three-dimensional finite element model.

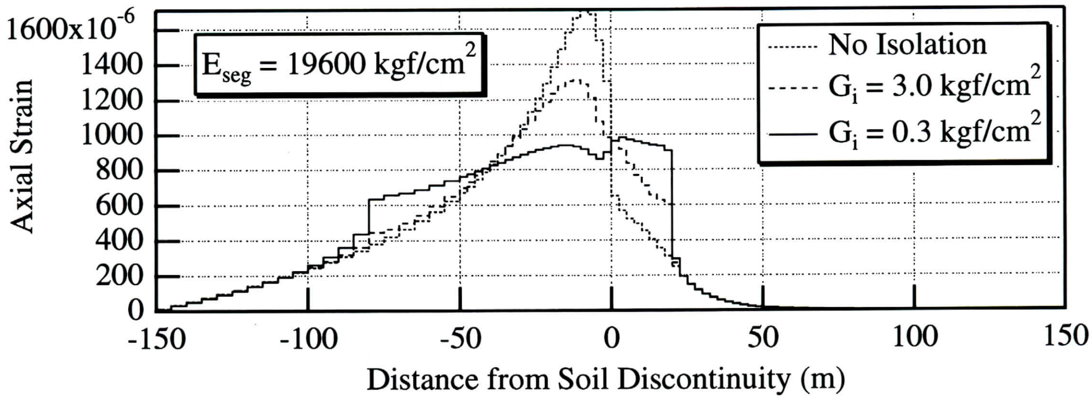


Fig.15 An example of the dispersion of tunnel strain due to the seismic isolation effect

CONCLUDING REMARKS

This paper has briefly described the results of numerical analyses and model vibration tests for identifying the effectiveness of seismic isolation applied to tunnels, as well as the study on the seismic design of tunnels. It was proved that adequate application of a seismic isolation layer provides reduction of tunnel sectional forces at a section where the ground conditions change abruptly, and that the sectional force reduction at a joint section with shafts by the seismic isolation system is far greater than that by the technique to use flexible segments, both of which have been proven promising for practical use. Given that the basic flow of the seismic design of tunnels has been consolidated, the authors intend to publish the results into a manual of design methods, apply the developed technology to practical construction works of seismic isolation tunnels to help prevent earthquake-related damage to lifelines.

ACKNOWLEDGMENTS

This study was conducted as part of the joint research between the Public Works Research Institute of the Ministry of Construction, the Public Works Research Center, and 17 private companies, under the title of "The Development of Seismic Isolation System for Underground Structures." The authors would like to express their deep gratitude to the members of the joint research program for their warm cooperation and helpful suggestions and discussions.

REFERENCES

1) Suzuki, T.: Model Vibration Tests on the Seismic Isolation Strucure for a Shield-driven Tunnel, Proc. 20th Earthquake Engineering Symposium, JSCE, pp.565-568, 1989. (in Japanese)

2) Unami, K. and Suzuki, T.: A Study on the Seismic Isolation Structure for a Shield-driven Tunnel (Confirmation of Isolation Efects by FEM), Proc. 44th Annual Meeting of JSCE, Vol.1, pp.1204-1205, 1990. (in Japanese)
3) Suzuki, T. and Unami, K.: A Study on the Seismic Isolation Structure for a Shield-driven Tunnel (Application to Earthquake Response Analyses), Proc. 44th Annual Meeting of JSCE, Vol.1, pp.1206-1207, 1990. (in Japanese)
4) Kawashima et al.: The Development of Seismic Design for Underground Structures, Joint Research Report No.29, PWRI, pp.208-235, 1989. (in Japanese)
5) Takeuchi M. et al.: Experimental Study on the Sectional Force Reduction in Cross-sectional Deformation of Shield-driven Tunnels due to Earthquakes, Proc. JSCE, No.483/I-26, 1994. (in Japanese)
6) Suzuki, T.: Damages of Urban Tunnels due to the Southern Hyogo Earthquake of January 17, 1995 and the Evaluation of Seismic Isolation Effect, CD-ROM of the Eleventh World Conerence on Earthquake Engineering, Acapulco, Mexico, 1996.
7) Otsuka H., Hoshikuma, J. and K. Nagaya: A Fundamental Study on Innovative Menshin System for Underground Structures, Proc. 6th U.S.-Japan Workshop on Earthq. Dis. Prevent. for Lifeline Systems, Osaka, pp.427-436, 1995.
8) Suzuki, T. and Tamura C.: Proposal of a Seismic Isolation Structure for Shield-driven Tunnels and the Method to Evaluate Its Isolation Effect, Proc. JSCE, No.525/I-33, pp.275-285, 1995. (in Japanese)
9) Suzuki, T. et al.: Experimental Study on the Silicone-based Material for Seismic Isolation System for Urban Tunnels, Proc. JSCE, No.534/VI-30, pp.69-76, 1996. (in Japanese)
10) Tamura C., S. Okamoto and M. Hamada: Dynamic Behavior of a Submerged Tunnel during Earthquakes, Report of Institute of industrial Science, University of Tokyo, Vol.24, No.5, 1975.
11) Suzuki, T.: The Extended Quasi-three-dimensional Ground Model for Irregularly Bounded Surface Ground, Structural Engineering/Earthquake Engineering, Vol.9, No.1, pp.21s-32s, 1992.
12) PWRI: Joint Research Report on the Development of Seismic Isolation System for Undergroud Structures (PART-1), 1996.
13) PWRI: Joint Research Report on the Development of Seismic Isolation System for Undergroud Structures (PART-2), 1997.