

PROCEEDINGS OF THE
SECOND WORLD CONFERENCE ON
STRUCTURAL CONTROL

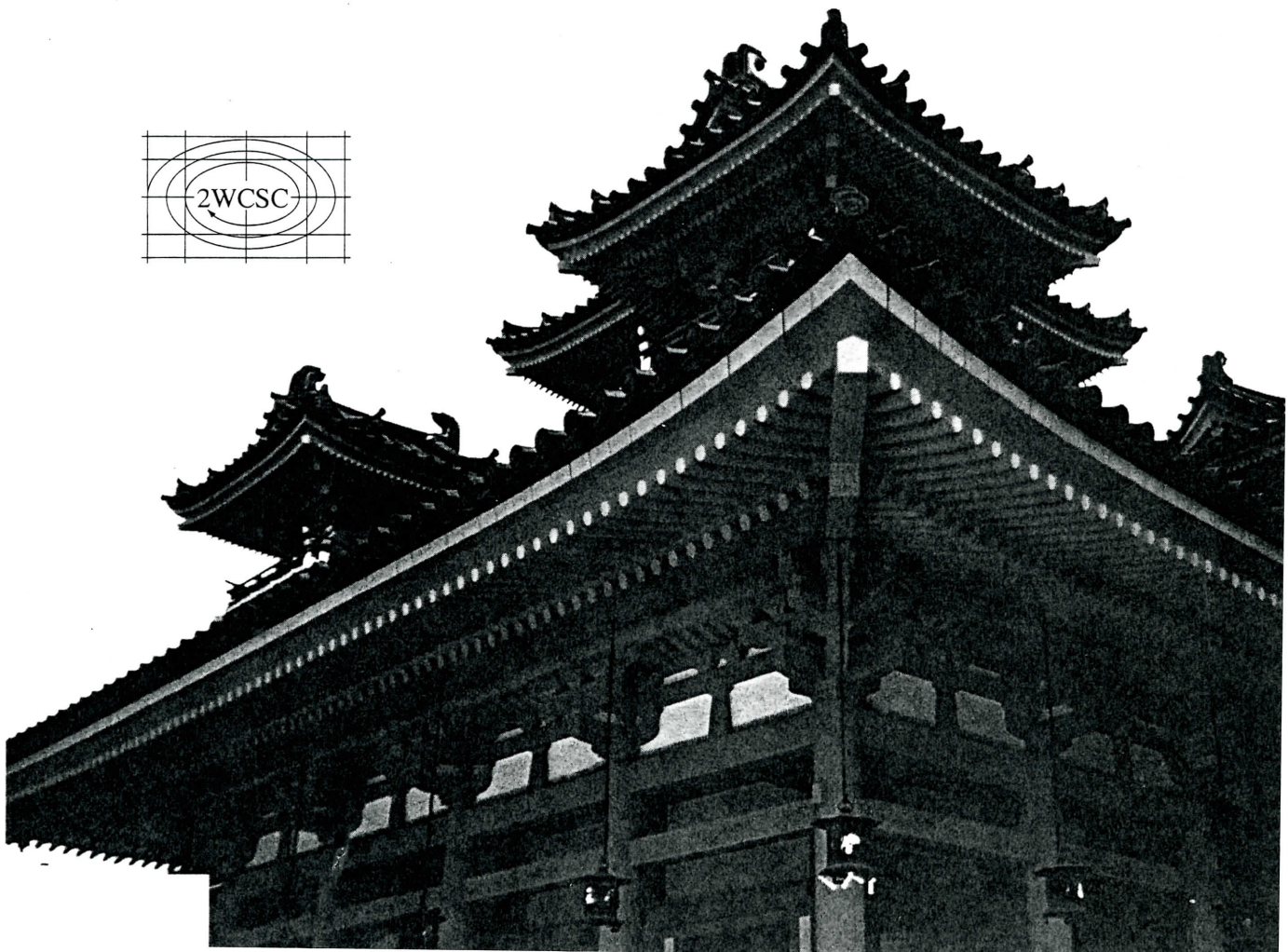
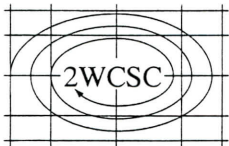
Kyoto, Japan

Volume 2

Edited by

Takuji Kobori | Yutaka Inoue | Kazuto Seto

Hirokazu Iemura | Akira Nishitani



Seismic Response Control of Underground Structures Using Seismic Isolation Design Concept

**Shigeki UNJOH¹⁾, Jun-ichi HOSHIKUMA²⁾, Kazuhiro NAGAYA²⁾,
Kazuhiko MURAI³⁾ and Takeyasu SUZUKI⁴⁾**

¹ *Head, Earthquake Engineering Division, Earthquake Disaster Prevention Research Center,
Public Works Research Institute, Ministry of Construction, Tsukuba, Japan*

² *Research Engineer, ditto*

³ *Visiting Research Engineer, ditto*

⁴ *Group Manager, Earthquake Engineering Research Group, Technical Research & Development
Institute, Kumagai Gumi Co., Ltd, Tsukuba, Japan*

ABSTRACT

Public Works Research Institute has conducted 3-year joint research program on seismic isolation systems for underground structures to improve the structural performance and the safety during earthquakes. This project has been made through the joint research program between Public Works Research Institute, Public Works Research Center and 17 private companies. Developed seismic isolation systems for the underground structures are made by constructing the isolation materials with low-shear modulus around the underground structures to absorb the effect of ground deformation. Five kinds of seismic isolation materials have been developed and the analysis and design methods for the underground structures with the seismic isolation systems have been also studied and developed.

1. INTRODUCTION

Underground structures such as tunnels and pipelines are generally affected by the displacement and deformation of the surrounding ground during earthquakes. In general, therefore, the underground structures are less influenced by the effect of earthquakes than the structures on the ground in which the earthquake response is amplified through the structures.

On the other hand, the underground has recently been starting to be developed and to be densely used especially in urban areas. The underground structures are often required to be constructed at the sites where the effect of earthquake becomes critical in the design, such as the sites with soft soil conditions, the sites where the ground condition is

drastically changing, and the sites where structures with different vibrational characteristics are constructed closely or jointly.

During the 1995 Hyogo-ken-nanbu Earthquake, the damage to the underground structures were relatively slight comparing the structures on the ground such as buildings and bridges. However, some of the underground structures such as subway station were damaged destructively. At the Daikai-Station of the Kobe High Speed Train, the RC columns were failed in shear and the upper slab was settled.

The damage to sewage systems such as cracks and dislodgement of pipes were also found. The Public Works Research Institute has been studied and developed the seismic isolation systems for the underground structures to improve the seismic performance and the safety by constructing the isolation materials with low-shear modulus surrounding the underground structures. The isolation materials absorb the deformation of the ground during the earthquakes. This study was made through the joint research program between Public Works Research Institute, Public Works Research Center, and 17 private companies including material makers, general contractors, design consulting firms.

In the Joint research program, major objectives of the research and development are as follows:

- 1) Development of Isolation Materials Applicable for the Seismic Isolation Systems
- 2) Construction Methods of Seismic Isolation Materials
- 3) Design Methods for Underground Structures with Seismic Isolation Systems

The final accomplishments of the research and development is compiled as the "Draft Manual of Seismic isolation design for Underground Structures" in March 1998.

This paper presents the concept of the seismic isolation systems for the underground structures and the outline of the draft design manual.

2. SEISMIC ISOLATION SYSTEMS FOR UNDERGROUND STRUCTURES

2.1 Concept of Seismic Isolation Systems

In general, underground structures are subjected to the deformation through the interaction between the ground and the structures. Therefore, when the stiffness of the structures are increased, the flexibility of the structures is decreased then the section force developed against the same deformation is increased. Hence, the design to increase the section or number of reinforcing bars to ensure the earthquake force developed like usual structures is not effective in general. In this case, it is effective to isolate the structures from the deformation of the ground.

There are several ways to decrease the effect of ground deformation to be transmit to the underground structures. Major ways are the followings :

- 1) To make the underground structures flexible by decreasing the stiffness
- 2) To decrease the effect of ground deformation to be transmitted to the underground structures

The usual way, which has been employed for actual submerged tunnels and shield tunnels and common utility ducts, is the above 1) using flexible joints. When the stiffness of the joints are decreased, the ground deformation is absorbed at the joints and the

section force of the structures is decreased. However, when the displacement developed at the joints becomes excessive, there are cases in which such excessive displacement is not acceptable or the special water-proof joints are required depending on the performance level required to the structures during large earthquakes.

On the other hand, the above 2) includes the methods in which the seismic isolation layer consisted of the materials with low shear modulus comparing the surrounding soils are constructed around the structures as shown in **Fig.1**. Since the shear deformation of the ground is absorbed by the seismic isolation layer, the excessive displacement, which may be developed at the specific joints, is prevented by this methods. Furthermore, since the ground deformation is absorbed, the isolation layer is effective to earthquake ground deformation both in the longitudinal and transverse directions.

Here, the method to decrease the effect of earthquakes by constructing the seismic isolation layer around the underground structures is defined as "Seismic Isolation Systems for Underground Structures".

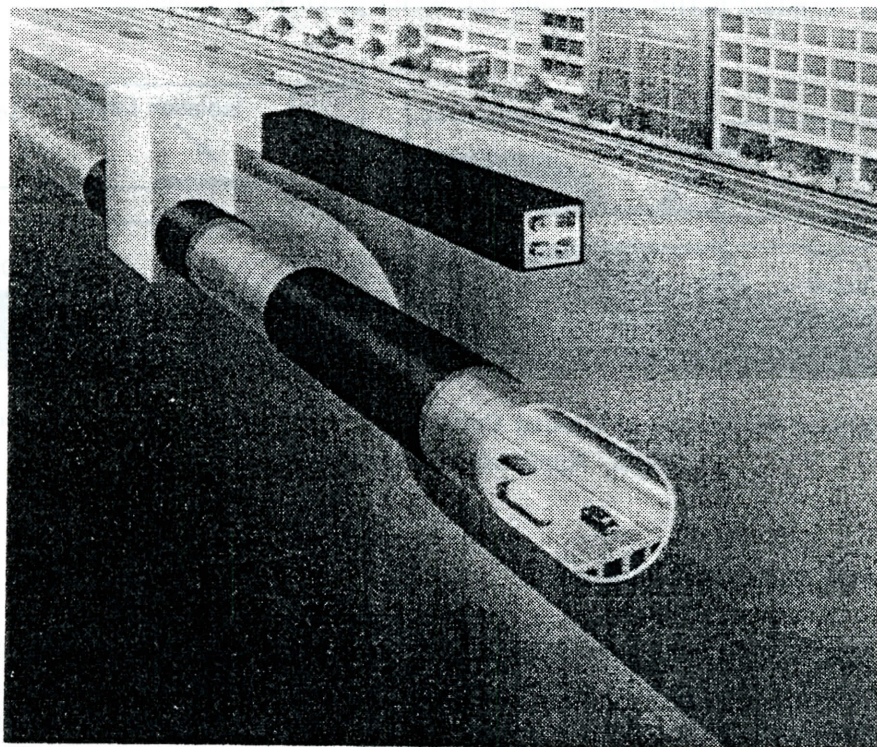


Fig.1 Concept of Seismic Isolation Systems for Underground Structures

2.2 Application of Seismic Isolation Systems

The effect of earthquake is generally large for the underground structures under the following conditions based on the past earthquake damage experiences.

- 1) Boundary section where the ground conditions are critically changed

The effect of earthquakes on the underground structures becomes large at the sites where the ground condition is changing from stiff ground to soft ground, or from cut ground to embanked ground. The deformation and the strain is concentrated at the boundary of the such sections with the change of ground conditions.

2) Connection section of two different structures

The deformation is concentrated at the connection section between shaft and tunnels, or junction sections, by the difference of the vibrational characteristics of two adjacent structures.

Therefore, the application of the seismic isolation systems is effective such boundary sections with different ground conditions or different structural conditions as shown in **Fig.2**. The concentration of the deformation and the strain is absorbed by the seismic isolation layer and the seismic performance of the underground structures can be improved.

Also, the transmission of shear deformation can be decreased by the seismic isolation layer, the effect of earthquakes is decreased for the transverse direction of the structures with wide section in which the surrounding shear stress is critical in the seismic design.

Furthermore, when it is required to prevent water from coming in the structure, depending on the required performance of the structures, the application of the seismic isolation layer with a water-proof function is effective both for the increase of the earthquake resistant performance and the water-proof performance.

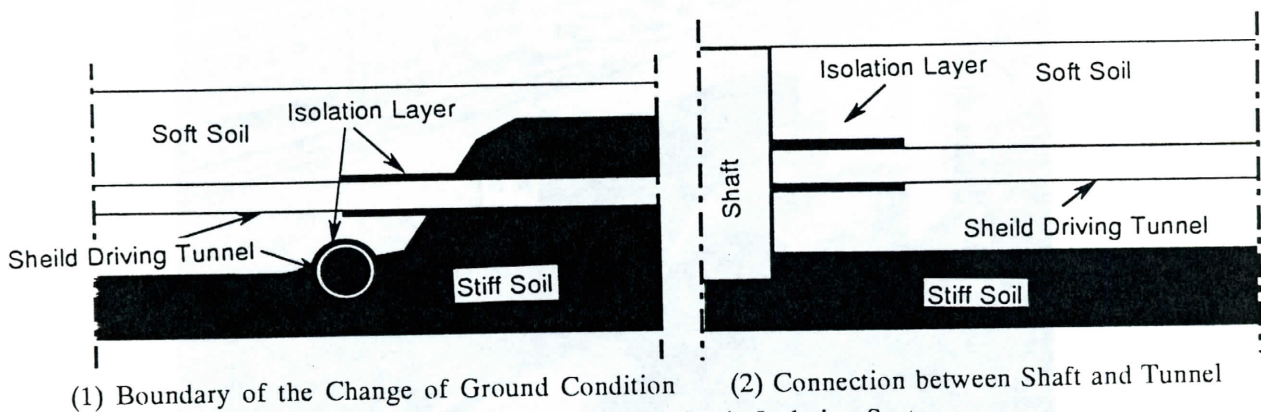


Fig.2 Application of Seismic Isolation Systems

2.3 Seismic Isolation Materials

Seismic isolation materials applicable to the underground structures are required to have the performances of seismic isolation functions and the function as the backfill materials. The development of the seismic isolation materials have been made for the shield-driving tunnels and the open-cut type tunnels. The required performances are as follows:

- 1) Low shear modulus and high shear deformability
- 2) High durability, long-term stability, and small volumetric changes
- 3) High constructionability (for example for shield-driving tunnels : transportability by pumping in a liquid state and high filling-up performance)
- 4) Watertightness
- 5) No dilution by ground water
- 6) No contaminants

Based on the above required performances, in the joint research program, 5 kinds of the seismic isolation materials were developed as shown in **Table 1**. The material characteristics including mechanical one, such as shear modulus, durability, watertightness, creep, and constructionability were tested using developed materials.

Table 1 Seismic Isolation Materials Developed

Construction Methods	Isolation Material	Material Contents
Shield Driving Tunnel	Asphalt-based Material	Asphalt and portland cement with high-water absorbing polymer
	Urethan-based Material	Urethan with fly ash and polyor
	Silicon-based Material	Silicon oil and fly ash with polyether
Open-Cut Type Tunnel	Liquid Rubber Material	Polybutadiene-type liquid rubber with polyisocyanate
	Precast Rubber Panel	Rubber tips made of shredded tires with urethan polymer resin

Fig.3 shows examples of the mechanical properties of the developed materials obtained through the hollow cylindrical cyclic shear tests. The all materials were tested by the same testing methods.

To simulate the actual condition in the tests, the surface soil layer with about 3m are assumed for the open-cut type tunnels. And for the shield driving tunnels, the surface layer with about 20 m was assumed. Then the confined pressures were selected as 0.5, 1.5 and 3.5 kgf/cm². The cyclic loading rate is assumed as 1 Hz considering the natural period of the surface layer. The strain range tested was assumed up to 10% considering the large deformation during the large earthquakes based on the analytical results.

Fig.3 shows that the shear modulus and damping ratio for Urethan-based material, Silicon-based material and Liquid Rubber material are almost constant in the range of the strain tested. And the confinement dependency was not found.

On the other hand, Asphalt-based material has the strain dependency in which when the strain increases the shear modulus decreases and the damping increases. The confinement dependency is found at the small strain range but is not remarkable.

For Precast Rubber Panel, the strain dependency and confinement dependency are found. Since the precast rubber panel is made by binding the rubber tips by resin, the precast rubber panel has the void inside the panel. The strain dependency is developed by the resin characteristics is changed in the high strain range then the shear modulus decreases.

Seismic isolation design of the underground structures has to be made based on the material characteristics as above mentioned. Some materials have other dynamic characteristics such as velocity dependency. They are also obtained through the necessary tests.

2.4 Construction Methods

Fig.4 shows the outline of the construction methods of seismic isolation materials. For the shield-driving tunnels, the same construction methods of the backfill to the tale void is applicable. The materials are injected to the tale void from the inside of the tunnels and the seismic isolation layer has constructed around the structures. To prevent the inflow of the isolation materials toward the shield machine and to construct seismic isolation layer

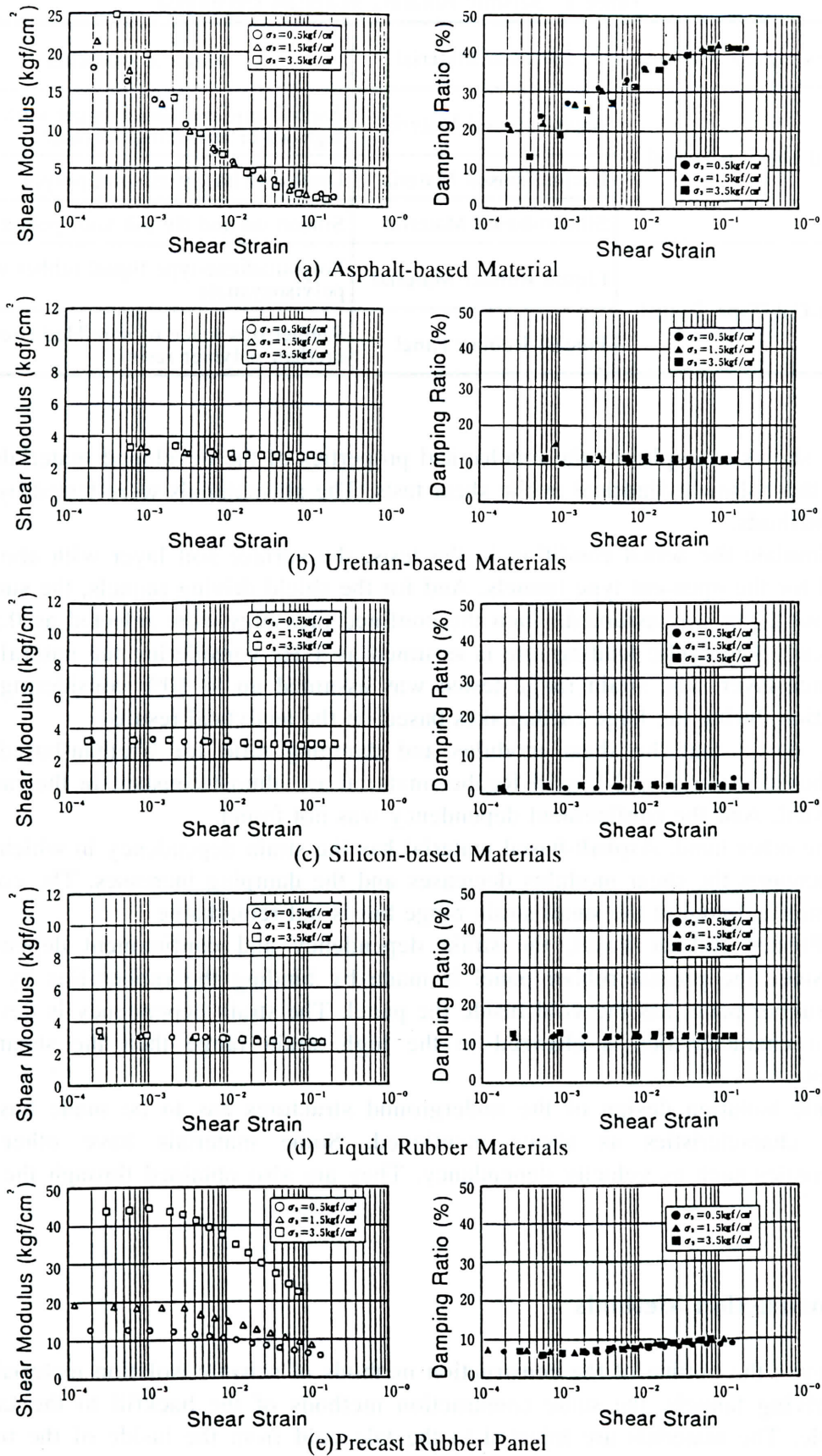


Fig.3 Dynamic Mechanical Properties of Seismic Isolation Materials Developed

certainly in the case void, the shield machine requires the inflow prevention devices but not important remodeling. For the open-cut type tunnels, the seismic isolation layer can be constructed with the construction of the tunnels. In the joint research project, both construction methods are verified through the construction tests of the seismic isolation layer.

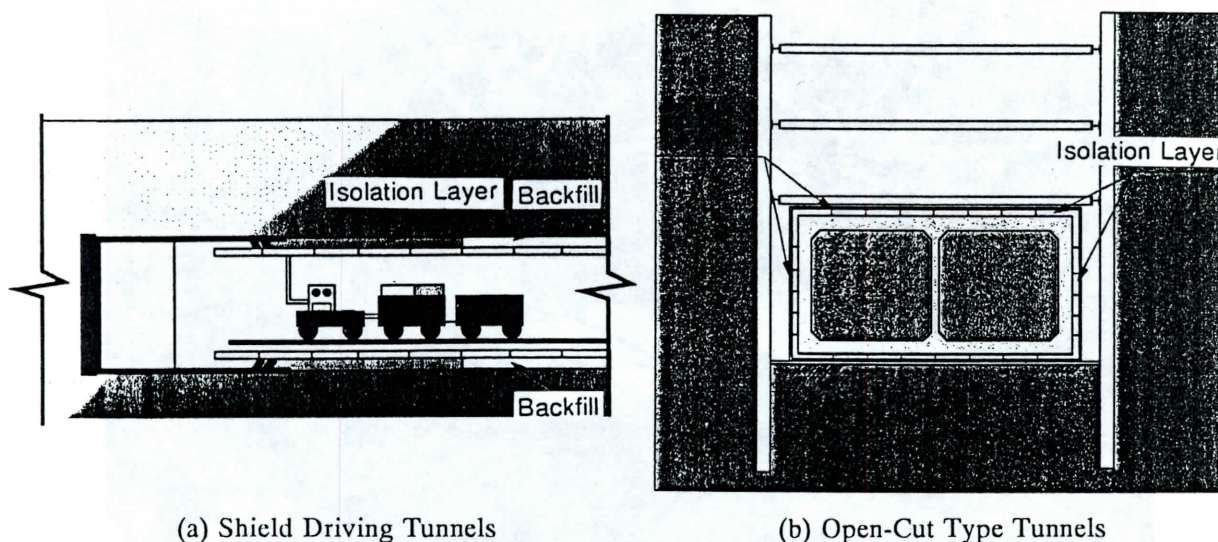


Fig.4 Outline of Construction Methods

3. VERIFICATION TESTS OF THE EFFECTIVENESS OF SEISMIC ISOLATION SYSTEMS

3.1 Test Models

To verify the effectiveness of the seismic isolation systems, the model tests were made using large shake table at the Public Works research Institute.

Fig. 5 shows the scale of the model. Tunnel is assumed to be constructed at the change section of ground conditions. The tunnel was the almost 1/70 size of actual structures with a diameter of 70mm and the thickness of 2mm. The ground was made of Silicon where the soft soil was assumed to have the shear modulus of 1kgf/cm^2 , and the stiff soil was assumed to have the 20kgf/cm^2 . Seismic isolation layer was assumed to have the thickness 10mm and the shear modulus of 0.05kgf/cm^2 .

The model was subjected to the sinusoidal ground motion and the random earthquake ground motion. Since the natural frequency of the model was 6.5Hz, the sinusoidal wave with the natural frequency of the ground was input to the shake table.

3.2 Test Results

Fig. 6 shows the typical test results. In the right side section where the ground condition is

changed, the seismic isolation layer is constructed. The strain in the tunnels in the longitudinal direction developed at the change section of the ground conditions was decreased by 30% by employing the isolation layers. This was the almost expected effectiveness through the analysis.

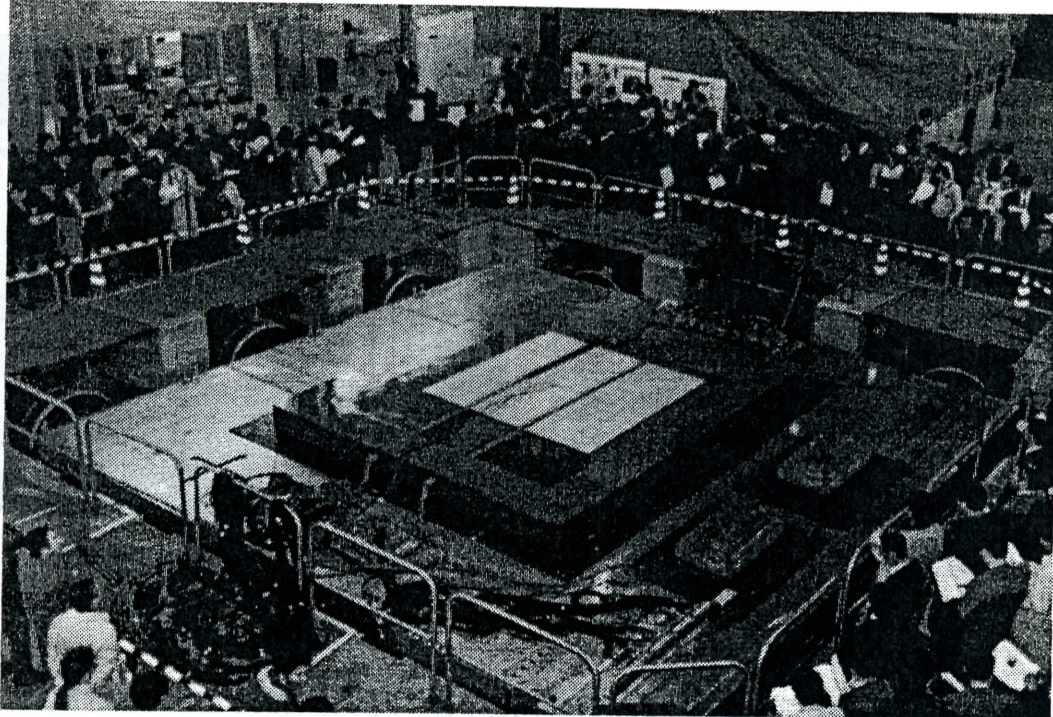
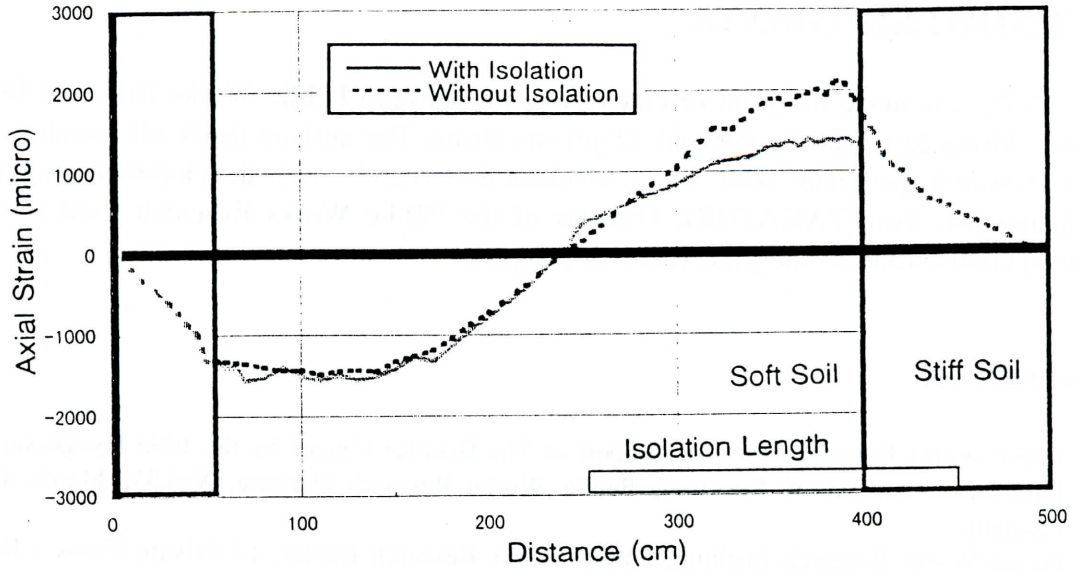


Fig.5 Model for Shake Table Tests

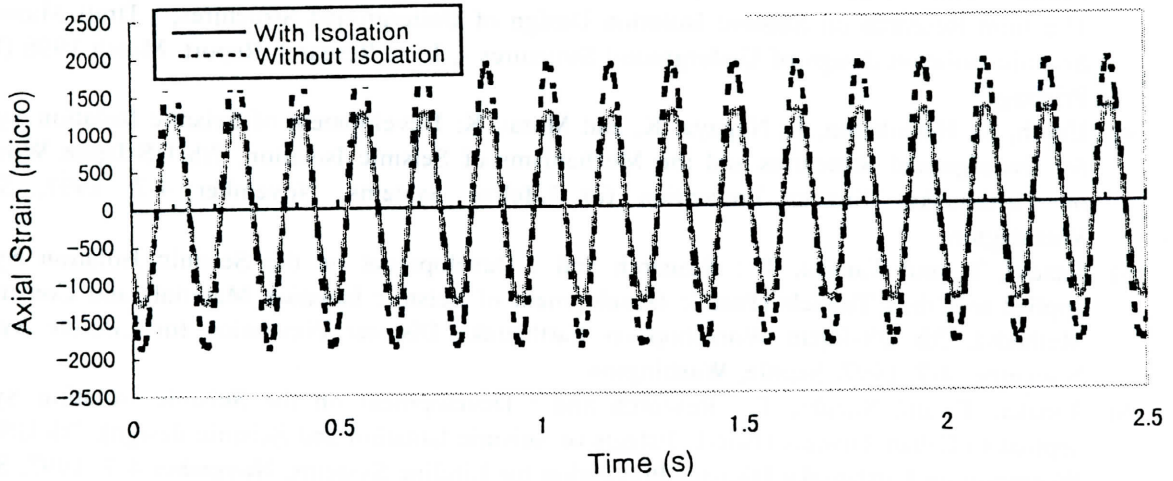
4. CONCLUDING REMARKS

The preceding pages presented an outline of 3-year joint research program on seismic isolation systems for underground structures to improve the structural performance and the safety during earthquakes. There is an idea of the seismic isolation system for the underground structures long time ago, but the isolation materials and the construction methods applicable for the systems had not yet been developed. Through the joint research program, 5 kinds of seismic isolation materials have been developed and the analysis and design methods for the underground structures with the seismic isolation systems have been also studied and developed. The final accomplishment is compiled as a "Draft Manual for Seismic Isolation Design of Underground Structures". Since the draft manual is now under printing, it will be available in around June.

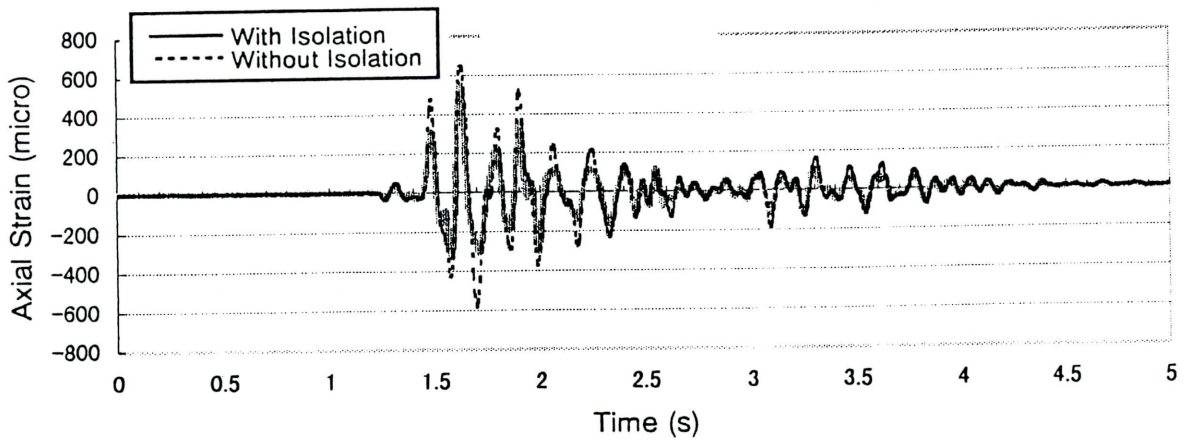
This research is one of the first steps to realize a new earthquake resistant structure. We are planning to study furthermore about the practical application of the isolation systems and the verification tests using full-scale structures should be studied.



(a) Strain Distribution in Tunnel Model in The Longitudinal Direction
(Sinusoidal Input : 6.5Hz, 150gal)



(b) Strain Response
(Sinusoidal Input : 6.5Hz, 150gal)



(c) Strain Response (Earthquake Wave)
Fig.6 Test Results of Shake Table Tests

ACKNOWLEDGMENTS

This study was made the joint research program between Public Works Research Institute, Public Works Research Center and 17 private firms. The authors thank all members of the joint research program who have conducted research and development eagerly. In particular, Mr. Isao TAKATORI, Director of the Public Works Research Center for their faithful contribution to the joint research program.

REFERENCES

- 1) Public Works Research Institute : Report of The Disaster Caused by the 1995 Hyogo-ken Nanbu Earthquake, Journal of Research, Public Works Research Institute, Vol.33, March 1997 (in English)
- 2) Public Works Research Institute, Public Works Research Center, 17 Private Firms : Report of The Joint Research on Seismic Isolation Design of Underground Structures Vol.1 and Vol.2, Joint Research Report, No.154 and 192, November 1996 and December 1997, (In Japanese)
- 3) Public Works Research Institute, Public Works Research Center, 17 Private Firms : Report of The Joint Research on Seismic Isolation Design of Underground Structures, - Draft Manual for Seismic Isolation design of Underground Structures -, Joint Research Report, March 1998 (Under Printing)
- 4) Unjoh, S., Hoshikuma, J., Nagaya, K, and Murai, K: Development of Seismic Isolation Systems for Underground Structures and the Mechanisms of Seismic Isolation, 7th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, November 4-7, 1997, Seattle, Washington
- 5) Suzuki, T, and Tanaka, T : Research and : Development on the Seismic Isolation Systems applied to Urban Tunnels (Part-1: Development of Seismic Isolation Materials and Construction Methods), 7th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, November 4-7, 1997, Seattle, Washington
- 6) Tanaka, T, and Suzuki, T : Research and : Development on the Seismic Isolation Systems applied to Urban Tunnels (Part-1: Effects of Seismic Isolation and Seismic design), 7th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, November 4-7, 1997, Seattle, Washington
- 7) Unjoh, S., Hoshikuma, J., Nagaya, and K, Murai, K: Draft Manual for Seismic Isolation Design of Underground Structures, 30th UJNR Joint Meeting, May, 1998, Gathersburg