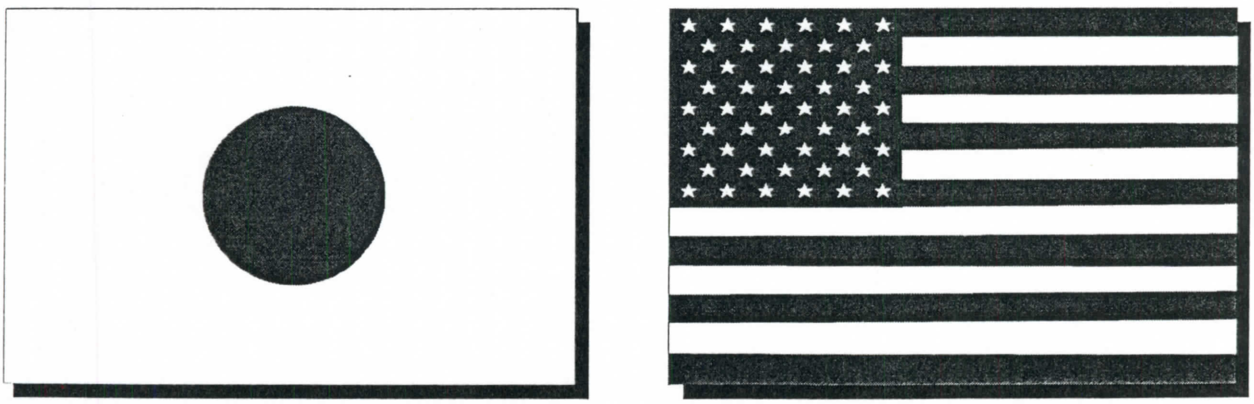
Wind and Seismic Effects

Proceedings of the 32nd Joint Meeting

NIST Special Publication 963

Stephen A. Cauffman, Editor



NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

1901-2001
NIST CENTENNIAL

DEVELOPMENT OF SEISMIC ISOLATION TECHNOLOGY FOR UNDERGROUND STRUCTURES AND THE APPLICATION

by

Shigeki UNJOH[1], Junichi HOSHIKUMA[2], Kazuhiro NAGAYA[3] and Takeyasu SUZUKI[4]

ABSTRACT

The seismic isolation for underground structures is the system in which a tunnel body is covered by a thin isolation layer consisting of elastic materials with low shear modulus. The isolation layer absorbs the strain transmitted from the surrounding soils during large earthquakes so that the seismic performance of underground structures be improved. The Public Works Research Institute has developed this new seismic isolation technology with the Public Works Research Center and 17 private companies from 1995-1998. Then the seismic isolation technology is applied for a practical constrction at the connection of vertical shaft and tunnel of common utility ducts firstly in the world. This paper presents the outline of the seismic isolation technology and the practical application.

KEY WORDS: Seismic Isolation
Underground Structures
Seismic Performance
Common Utility Ducts

1. INTRODUCTION

The Hyogo-ken Nanbu Earthquake of January 1995 damaged underground structures and some underground structures such as the collapse of the Daikai Station on the Kobe Rapid Transit Railway were heavily damaged. It is essential to guarantee the operation of communication, electricity, gas, water, and other lifelines in regions struck by powerful earthquakes. To achieve this goal, the safety from strong earthquakes of utility tunnels that are typical underground structures provided to concentrate these lifeline services is required to be preserved. And while the earthquake resistance of underground structures must be improved, the public is demanding that the cost of their construction be reduced.

To meet these needs, the Public Works Research Institute of the Ministry of Construction, the Public Works Research Center and 17 private companies have taken part in joint research to develop seismic isolation technology for underground structures as a new technology that can improve the earthquake resistance of underground structures over that provided by conventional technologies at the same time as it lowers construction costs [1)-3)].

The seismic isolation structure that was developed for underground structures is a structure that can sharply reduce the effects of earthquakes by forming a flexible seismic isolation layer around the outer periphery of an underground structure to insulate the underground structure from deformation of the surrounding ground.

This paper describes an outline of seismic isolation technology for underground structures and a practical application for the starting vertical shaft of the Nakagawa Utility Tunnel. An outline of the test construction of the seismic isolation structure as well as the field test to verify the seismic isolation functions are presented.

---

1) Head, Earthquake Engineering Division, Earthquake Disaster Prevention Research Center, Public Works Research Institute, Ministry of Construction, Tsukuba-shi, Ibaraki-ken, 305-0804, Japan
2) Senior Research Engineer, ditto
3) Research Engineer, ditto
4) Deputy Director, Techical Institute of Kumagai-gumi Corp., Tsukuba-shi, Ibarakli-ken, 300-2651, Japan (Underground Structure Seismic Isolation Technology Promotion Committee)

2. R&D OF SEISMIC ISOLATION TECHNOLOGY

Fig.1 shows a conceptual diagram of the seismic isolation structure. Seismic isolation mechanisms for underground structures are categorized under the following four items.

1) Blocking the transmission of strain during earthquakes from the surrounding ground to a tunnel structure

2) Smoothing the tunnel strain in the seismic-isolated structure (longitudinal direction)

3) Dispersing the stress resultant concentrated at the corners of rectangular section tunnels (lateral direction)

4) Insulating the vertical shaft body from the tunnel at the tunnel entrance and smoothing the tunnel strain in the seismic isolated section (at vertical shaft connection points)

The performance required by a seismic isolation layer capable of providing these mechanisms was studied from the perspective of its mechanical properties and construction properties, then the seismic isolation material was developed based on the results of the study. The development process included testing to corroborate the mechanical properties, durability, etc. of the seismic isolation material, testing to verify its construction properties by trial manufacturing a seismic isolation material injection system, and corroborative material injection trials in an actual tunnel. And to develop a seismic isolation structure construction method for shield tunnels, in addition to a seismic isolation structure for use at points where ground conditions change abruptly, a seismic isolation structure for vertical shaft connections that are points of abrupt change in the structure and a method of constructing such a seismic isolation structure have been proposed. A design method and construction method for seismic isolation structures for underground structures that has been established as a result of this joint research were published in September 1998 as the Underground Structure Seismic Isolation Design Method Manual (Draft) [3].

The joint research has clearly shown that the seismic isolation structure can be effectively applied in 1) the longitudinal direction at points of abrupt change in ground conditions, 2) where the lateral section of a rectangular tunnel changes abruptly, and 3) in the longitudinal direction at connections with vertical shafts, but the results of a cost-effect analysis show that the most promising application of this seismic isolation structure is at the connections with vertical shafts of a shield tunnel.

The conventional method of providing seismic protection at connection with vertical shafts of a shield tunnel has been the application of a flexible segment. A flexible segment is a single special segment ring constructed so that it concentrates and absorbs strain generated in the surrounding tunnel. A flexible segment can absorb tunnel strain that is locally concentrated at the location where it is installed, but its effects are generally limited to a small range. But if a vertical shaft is isolated from a segment by a seismic isolation layer at the same time as a seismic isolation layer is installed within the range where the ground strain is most concentrated for about 10 m from the shaft, it is possible to provide isolation from both a point of abrupt change in the structure and from concentrated ground strain. In this way, the tunnel stress resultant can be reduced in a short seismic isolation section [4].

3. PRACTICAL APPLICATION OF DEVELOPED SEISMIC ISOLATION TECHNOLOGY

3.1 Outline

The seismic isolation structure for underground structures has progressed to the research and development stage, but because it has still not reached the stage where it is a practical design and execution technology, an actual structure must be designed and a trial execution of this design performed.

In 1997, initial seismic design for L1 earthquake motion was performed for the vertical shaft connection point of the No. 1 Nakagawa Utility Tunnel (below referred to as "Nakagawa Utility Tunnel"), and a flexible segment was chosen for the start side and a flexible joint for the arrival side of the connection point. The Nagoya

National Highway Construction Office of the Chubu Regional Construction Bureau of the Ministry of Construction applied the field trial system, the connection was redesigned to provide seismic resistance capable of withstanding L2 earthquake motion one rank higher than the previous design, and to confirm the applicability of the new system in actual tunnels and execution costs, this seismic isolation technology was selected for execution on the No. 1 Nakagawa Tunnel in 1997. This was the first attempt to use this seismic isolation structure anywhere in the world.

3.2 Seismic Isolation Design of Vrtical Shaft Connection

(1) Structure Conditions

Fig.2 shows the surface ground structure at the start side of the vertical shaft and the locational relationship of the vertical shaft and tunnel. The bottom plate of the vertical shaft is in a diluvial clay layer, and the SMW wall diaphragm that surrounds it extends for about 40m down to a diluvial sandy soil layer. The earthquake wave input bedrook and the bedrock of the axisymmetric finite element method model for this design were assumed to be the top of the diluvial sandy soil layer Ds_3 (V_s = 320m/s) at a depth of 30.9m in the figure. The figure also shows the mechanical physical properties during slight strain of the surface ground.

The vertical shaft is a reinforced concrete structure with external width of 14m and depth of 10.8m and the plane shape shown at the top of **Fig.2**. Its wall thickness varies somewhat according to the depth and it has partition walls, but because the overall shear stiffness is not effected by accounting for these, it was assumed to be a box-shaped structure with a constant wall thickness of 14m for this study. The modeling of the vertical shaft by an axisymmetric finite element method model included the modeling of not only the vertical shaft body, but also the wall diaphragm constructed by SMW as part of the vertical shaft.

The tunnel studied was a shield tunnel with an exterior diameter of 5,050mm made of reinforced concrete segments with a thickness of 250mm, it was constructed by the slurry shield method (external diameter of the shield machine: 5,190mm), and its segment ring joints were connected with long bolts. The tension stiffness of the shield tunnel was modeled using equivalent tension stiffness calculated from the spring of the segments and from the serial spring of the spring of the ring joints. The compression stiffness used was the compression stiffness of the concrete of the segments.

Because the external diameter of the shield machine was 5,190mm, the thickness of the isolation layer was set at 7cm that equals the thickness of the tail void.

The verification of safety during an earthquake of the shield tunnel was performed based on two factors the allowed aperture of the ring joint (2mm) and the yield stress of the joint bolts (940N/mm^2) during tension deformation, and based on the allowed compression stress (24N/mm^2) of the segments during compression deformation.

(2) Input Earthquake Motion

The input earthquake motions for L2 earthquake motion were chosen from among standard waves used for seismic design of highway bridges. Waves obtained by performing amplitude compensation of the component at right angles to the bridge axis of the Kaihoku Bridge during the Miyagi Prefecture Offshore Earthquake of 1978 were used as Type-1 earthquake motion for category I ground. Waves obtained by performing amplitude compensation of the NS component recorded at the Kobe Marine Meteorological Observation Station during the Hyogo-ken Nanbu Earthquake of 1995 were used as the Type-2 earthquake motion. **Fig.3(1)** shows the Type-1 earthquake motion and **Fig.3(2)** shows the Type-2 earthquake motion. The one-dimensional seismic response analysis of the surface ground was performed by the substitute structure approach: considering these input earthquake motions to be waves observed at the outcrop of free rock, reducing the amplitude by 50%, and inputting the resulting waves from the top of the bedrock layer D_{s3}. The strain dependency of the ground used for the analysis was obtained from a mean strain dependency evaluation equation for typical ground [5) 6)].

The ground inertial force applied by the axisymmetric finite element method model was calculated by the ground response seismic coefficient method[7] that uses the ground acceleration at the time when the maximum value of the total of the shear strain of the ground from the bed rock to the surface is generated based on seismic response analysis.

(3) Design Results

Fig.4 shows the results of a parametric study of deformation during tension subject to strict design conditions that was conducted to determine the shear modulus of rigidity of the seismic isolation layer and the length of the seismic isolation section. The variables for the parametric study were shear modulus of rigidity of the isolation layer of 0.3 and 0.5N/mm^2 and the length of the seismic isolation section from the exterior wall of the vertical shaft that were 10, 15, and 20m. The shearing modulus was set considering silicon seismic isolation material (SISMO-003 or SISMO-005) that is isolation layer material with superior durability and workability. Analysis results have revealed that within a seismically isolated section length between 10m and 20m, there is little variation in the tension axial force of the tunnel and that even if the shearing modulus of the seismic isolation layer is reduced from 0.5N/mm^2 to 0.3N/mm^2, the tension axial force of the tunnel declines very little. The shearing modulus of the seismic isolation layer was, therefore, set at 0.5N/mm^2 and the seismically isolated section length was set at 10m from the exterior wall of the SMW.

Fig.5 shows an example of the results of an analysis of the joint aperture during tension deformation caused by Type-1 earthquake motion. In addition to showing the results for a seismic isolation structure case, the figure presents the results of an analysis of a rigid connection case and of a case hypothesizing a flexible segment with a Young's modulus of 0.1N/mm^2 at a point 1 m from the external wall of the vertical shaft. If a seismic isolation structure is adopted in this way, the ring joint aperture will be within the allowed value (2mm), but in the cases hypothesizing the adoption of a rigid connection and a flexible segment, the aperture exceeded the allowed value. The tension stress of the joint bolts was within the range of the allowed values for all cases.

Fig.6 shows the results of an analysis during compressive deformation. This figure shows that under both types of earthquake motion, the compressive stress of the segment was within the allowed value (940N/m^2) for all cases. It also reveals that adopting the seismic isolation structure lowers the compressive axial force on the segment to about half that obtained with the rigid connection method, which is larger than the reduction to 2/3 possible with a flexible segment.

Fig.7 is a schematic diagram of the seismic isolation structure at the start vertical shaft established by the above seismic isolation design process. The design calculations modeled the SMW and the vertical shaft body as a vertical shaft. The seismic isolation section that was analyzed extended for 10m from the external wall of the vertical shaft, but for execution reasons including the fact that the segment length is 1.2m, the seismic isolation layer was formed in the tail void for 10 rings from the tunnel entrance. This means that the seismic isolation section extended 9.6m from the external wall of the SMW and 10. 5m from the external wall of the vertical shaft body. On the ground side of the SMW wall, the seismic isolation layer was 7cm thick that is the same as the tail void, but it was thicker at the entrance. And to provide the tunnel entrance with waterproof properties and to insulate the vertical shaft body from the segment, a natural rubber ring with a wedge-shaped section, covered on three sides by water-absorbing rubber, and with a shearing modulus of 0.6N/mm^2 (tunnel entrance insulation layer) was installed at the tunnel entrance and integrated with the tunnel entrance concrete.

The adoption of a seismic isolation structure as described above, provides an existing structure with the ability to withstand Type L2 earthquake motion. And the waterproofing function of the silicon seismic isolation material guarantees waterproofing even if an unpredictable joint aperture occurs.

3.3 Practical Construction

(1) Isolation Material

The seismic isolation material used for the trial execution was silicon seismic isolation material SISMO-005 with its shearing modulus G adjusted to 0.5N/mm^2 or less. Silicon type seismic isolation material is a rubber elastic body hardened at normal temperatures by the condensation reaction caused by mixing and agitating fluid A that is a mixture of silicon polymer + finely powdered silica and fly ash with fluid B that consists primarily of a hardener and plasticity adjustment agent at a mix ratio by weight of 10:1. A cross linking agent is added uniformly to fluid A and a catalysis is added to fluid B. It is, therefore, possible to control only the hardening time without altering the hardness of the rubber that is the seismic isolation material by adjusting the quantity of the catalyst in fluid B. The seismic isolation material is an inorganic material based on silica and is both non-polluting and durable. **Fig.8** shows the strain dependency of the shearing modulus of the seismic isolation material obtained by cyclic hollow cylindrical cyclic shear testing performed at a loading frequency of 1Hz. This test shows that the seismic isolation material has stable dynamic physical properties regardless of the shearing strain. The material has no constraining pressure (depth) dependency and it is an elastic material with a damping factor less than 3%[8].

Fluid A is supplied to the agitator (capacity 1.8m^3) of the plant from a hopper located above the ground, then it is pressure fed from the agitator at a fixed rate by a mono-pump. Fluid B is supplied to the fluid B agitator (capacity 0.2m^3) of the plant from a drum, then it is pressure fed from the agitator at a constant rate by a mono-pump. The tip of the injector is a rubber injector used for backfill injection. After the two fluids have been mixed, a quarrying column mixer is passed through a 2-inch steel pipe for a total of 80 cm and its pressure loss is utilized to completely mix the fluids. Because this mixer is long and it is difficult to work with, the injector unit and mixer are connected by a flexible rubber tube.

The specific gravity of the seismic isolation material is 1.36, and its elongation is 100%. As stated above, the mix proportion was designed to lower the shearing modulus to less than 0.5 N/mm^2. Therefore, when the seismic isolation material is shipped from the factory, it provides JIS hardness of 32 degrees and a shearing modulus of 0.44N/mm^2 and satisfies the required physical properties after it has been blended indoors based on the stipulated mix proportion and is cured for one week at a temperature of 20 Centi-Degree.

(2) Construction

The level difference between the injection pump and injection outlet was minimized, care was taken to obtain a stable blend of fluid A and fluid B, and the seismic isolation material plant was installed in an intermediate level of the vertical shaft. **Fig.9** is a schematic diagram of the seismic isolation structure at the start side of the vertical shaft. As shown in the figure, the seismic isolation material was, in principle, injected during excavation from injection holes in the segments into the tail void produced as the shield excavator advanced in the same way as immediate backfilling injection is performed. It was feared that during the seismic isolation material injection work, seismic isolation material might flow into the blades where it would get into the chamber. To prevent this from occurring, as the shield excavator advanced, void filling clay (clay shock) was injected into the void between its steel shell and the natural ground from an injection outlet installed near the articulation of the shield excavator to block the gap between the tail void and the blade. Because the clay shock was pressure injected into small voids on the excavated natural ground, it also prevented the seismic isolation material from leaking into the natural ground.

At locations in the fluid A and fluid B pressurized feed hoses just before their respective injection and mixing locations, bypasses were installed to cycle the two fluids through agitators prior to injection in order to prevent separation of their materials and a decline in their viscosity. To form a seismic isolation layer of uniform thickness around the segments, it was vital to exercise strict control of the excavation. It was necessary to guarantee that the seismic isolation work would not conflict with the basic principles of shield work that require the immediate filling of the tail void to prevent the collapse of the natural ground and to keep out ground water and mud. To guarantee this, before the work began, the segments were equipped with injection holes at three locations in the tunnel axis direction that differs for each segment piece, and injection was begun from the injection hole closest to the void, to permit the restarting of excavation after it was stopped because of trouble with the work.

That part of the work to form the seismic isolation structure at the vertical shaft connection that was most important and had to be done with the greatest care was the work at the entrance: the first stage in the execution. Because a large void is formed behind the segment at the entrance as shown in **Fig.9**, it was first stabilized by filling it with high density mud. After excavation to the third ring, clay shock was injected to fill the void behind the steel shell of the shield excavator to prevent the seismic isolation material from flowing into the blades, then the injection of the seismic isolation material at the entrance was performed.

(3) Quality Control

To control the quality of the seismic isolation material, the hardness of a hardened sample of the seismic isolation material made at the time it was shipped from the factory and the hardness of hardened samples made before, during, and after injection were measured by the JIS-K6301-A method. The flow rates of the seismic isolation fluid A and fluid B were controlled by installing Coriolis flow meters, and the quantities of fluid A and fluid B remaining in their respective tanks after the injection work were measured to confirm that the fluids were completely injected.

While the mean hardness of the seismic isolation material when it was shipped from the factory was 32, the hardness of samples of seismic isolation material obtained at the tip of the injector immediately before, during, and after injection and cured for 1 week ranged from 26 to 33 and the mean value was 29. Converting this to the shearing modulus obtained a result of 0.39N/mm^2, which is a little lower than the results of the measurements at the factory (hardness of 32, shearing modulus 0.45N/mm^2). The mean hardness of the seismic isolation material after 1 month passed, was 31 (G = 0.42N/mm^2), a result that fully satisfied the design value of G = 0.5N/mm^2 or less.

(4) Field Test for Effectivenes Verification

To verify the seismic isolation performance of the seismic isolation structure formed at the vertical shaft connection by this trial execution, a field experiment was carried out to measure the shear reaction force in the tunnel axis direction of the seismic isolation layer. When a seismically isolated shield tunnel surrounded by a seismic isolation layer is forcefully deformed in the tunnel axis direction, shear resistance proportional to the shear reaction of the periphery of the tunnel is obtained. Because this shear reaction force is the shear resistance of the seismic isolation layer and the ground around it, it is possible to evaluate it based on their series spring system. If the shearing modulus of the seismic isolation layer is more than 2 orders smaller than that of the ground, it is possible to approximate the shear reaction force of the seismic isolation layer body that treats the ground as a rigid body. Consequently, using the reaction force of the wall of the vertical shaft, the tunnel was moved towards the cutting face along with the shield excavator by a hydraulic jack, and the shear spring constant of the seismic isolation layer was estimated from the relationship of the tunnel axial direction deformation with the thrust of the hydraulic jack.

The shear spring constant of the seismic isolation layer can be obtained theoretically by Eq.2 from the relationship between the force and the displacement produced by treating the periphery of the seismic isolation layer as a constant condition and forcefully deforming the external surface of the tunnel in the tunnel axial direction.

$$K_m = 2\pi * G_m / \ln (R_m/R_i) * L \qquad (1)$$

Where:

- K_m: shear spring constant of the seismic isolation layer
- G_m: shear modulus of the seismic isolation layer
- L: length of the seismic isolation layer

R_m: 1/2 of the external diameter of the seismic isolation layer

R_t: 1/2 of the external diameter of the tunnel

Because it was necessary to complete the injection of the seismic isolation layer at the starting vertical shaft connection to form the seismic isolation then perform this test before the backfill injection that accompanies normal shield excavation, the test was performed four days after the final day of the seismic isolation material injection work.

Fig.10 is a schematic diagram of the seismic isolation layer reaction force measurement test. The reaction receiver installed on the vertical shaft body wall was a mobile structure that allowed the removal of the bolts to cause the temporary segment reaction frame to slide towards the tunnel. The reaction receiver was equipped with a pedestal to be used to install eight hydraulic jacks. By removing its bolts and installing jacks on the pedestal, the reaction receiver becomes a loading device structurally equipped with a movable reaction frame. As stated above, the periphery of the shield excavator is filled with clay shock and it is assumed that the shear resistance of the periphery of the shield excavator is low. It was, therefore, possible to move the segment in the direction of the cutting face along with the shield excavator to the location where the shear reaction force of the seismic isolation layer and the jack thrust were in balance, by advancing the hydraulic jacks installed on the reaction receiver and at the same time, adjusting the cutting face slurry pressure downwards to prevent the action of the jacks from increasing this pressure to maintain it at a constant level.

The jacking pressure was increased at steps of 50kN steps per jack for a total of 400kN per step. The jacking pressure was increased again after the tunnel deformation caused by the previous increase in thrust had stabilized. The loading was concluded when the tunnel had been deformed 10mm towards the cutting face. The unloading was performed in the same way as the loading: reducing the pressure applied by the jacks by 400kN, waiting for the tunnel deformation to stabilize, then lowering the pressure by another 400kN step. When the hydraulic jack pressure was down to zero, the residual displacement of the tunnel was measured. The jacks were operated from an intermediate level in the vertical shaft at a location where the operator could see the loading device equipped with the movable reaction frame.

The cutting face slurry pressure was automatically regulated so that it remained at a constant level of 0.15MPa (reaction of 3,200kN to by the slurry pressure) throughout all loading and unloading steps. But during the loading steps, the cutting face slurry pressure temporarily rose to a maximum of 0.17MPa and it took time to lower it to its stable value. But during unloading, the cutting face slurry pressure remained stable at almost exactly 0.15MPa, with the result that the pulling phase of the loading operation did not take as long as the pushing phase.

The measurements were performed by monitoring the pressure and stroke of the 8 hydraulic jacks, the relative axial direction displacement of the segment and the vertical shaft body on the left and right sides of the vertical shaft entrance, and the cutting face slurry pressure in the central control room, and by measuring the distance between the vertical shaft and the ring 1 joint of the segment closest to the cutting face using a light measure system fixed at the vertical shaft portal. The data obtained from these measurements was displayed to the operator in the intermediate level of the vertical shaft and used to make jack operating decisions. It was also monitored and recorded in a measurement vehicle located at ground level.

(4) Test Results

Fig.11 summarizes the results of the test in terms of the relationship of the relative axial direction displacement of the tunnel and the vertical shaft body wall at the entrance with the total thrust P_t of the 8 jacks installed on the reaction frame. The hysteresis in this figure is categorized as 5 loading states from I to V to explain the process of determining the shear spring constant of the seismic isolation layer. While the behavior varied according to the loading stage as shown in **Fig.11**, the tunnel stopped at location F with residual displacement of approximately 1.57mm without being restored to its original position even after the jack pressure was finally reduced to zero at the end of the unloading steps.

With the residual displacement of the tunnel at location F represented by δ cm, the shear spring constant of the seismic isolation layer by K_m (kN/cm), the maximum static friction force of the temporary segment and the pedestal by P_{static}, and the cutting face pressure produced by the cutting face slurry pressure by P_{mud}, and assuming that the cutting face slurry pressure can be ignored because in static state, it is balanced with the slurry pressure, the following equation of equilibrium can be established for the point in time where the tunnel has stopped at the final stage.

$$K_m = \delta \quad + P_{mud} = P_{static} \tag{2}$$

It can be concluded that because the residual displacement δ = 0.157cm, the maximum static friction force is in balance with (reaction force P_{mud} produced by the cutting face slurry pressure = 3,200kN) + (reaction force of the seismic isolation layer equivalent to the shear deformation of 0.157mm). Next, if it is assumed that the point A in **Fig.11** corresponds to the time when the temporary segment began to slide on the top of the pedestal, the maximum static friction force P_{static} = 4,570kN, and if these values are substituted in equation (2), K_m (kN/cm) is as shown below.

$$K_m = 4{,}570 \quad 3{,}200/0.157 = 8{,}730 \tag{3}$$

The thick dark line in **Fig.11** shows the results of assuming that P_{static} = 4,750kN and K_m = 8,730kN/cm to estimate the hysteresis relationship of the jack thrust with the axial displacement of the tunnel when the reaction force at the cutting face is assumed to be constant. The hysteresis that was estimated shows a separation from actual behavior caused by instability of the cutting face soil pressure at loading stage III [15], but the fact that both conform closely at loading stage II and at V that was the final stage of the unloading and an almost linear load displacement relationship was obtained during unloading reveals that a seismic isolation layer with reliable resilient behavior was formed around the periphery of the tunnel and its spring constant K_m = 8,730kN/cm.

Because the mean injection rate of the seismic isolation material was approximately 120%, the seismic isolation layer corresponding to this injection rate is 8cm, and the theoretical value of the shear spring constant of the seismic isolation layer with a shear modulus G = 0.5N/mm^2 is 11,380kN/cm^2 based on Eq.(1). Because the measured shear spring constant of the seismic isolation layer is 8,730kN/cm, the shear modulus of the seismic isolation layer is 0.383N/mm^2, which conforms almost perfectly with the mean value of 0.39N/mm^2 of the seismic isolation material injected as described above following 1 week of aging. The shear spring constant and the shearing modulus of the seismic isolation layer are, therefore, appropriate values.

Because as described above, elastic behavior capable of restoring the tunnel to its original position during unloading in a linear relationship with the jack thrust was obtained and because the shearing modulus of the seismic isolation layer is an appropriate value, it has been verified that a seismic isolation layer with the intended functions was constructed.

4. CONCLUDING REMARKS

This paper has summarized the design and execution of a seismic isolation structure for underground structures that has been made at the start vertical shaft connection of an actual shield tunnel.

(1) The trial execution of the seismic isolation structure verified the execution properties of the silicon seismic isolation material injection system.

(2) The mean injection rate of the seismic isolation material is 120%, which is a rate lower than the injection rate of normal backfill.

(3) In-situ testing conducted to measure the reaction force of the seismic isolation layer verified the functions of the seismic isolation structure by demonstrating that elastic behavior capable of restoring the tunnel to its original position during unloading in a linear relationship with the jack thrust could be obtained and that

the shearing modulus of the seismic isolation layer obtained by the test conforms with measured values.

(4) The above results have shown that this seismic isolation structure for underground structures is a technology that can be applied to the design and execution of actual underground structures.

ACKNOWLEDGEMENTS

The construction of the seismic isolation structure was performed with the generous assistance and cooperation of the staff of the Nakagawa Shield Tunnel Construction Office, Hazama-Sato Joint Venture under the contract of Nagoya Construction Office of Ministrry of Construction. The authors wish to conclude by expressing their sincere gratitude to them for their contribution to this project. The members of the Underground Structure Seismic Isolation Technology Promotion Committee provided technical advice regarding the planning and the design of the trial execution. The authors wish to also thank them for their assistance.

REFERENCES

1) Public Works Research Institute, et. al.: Report on Joint Research on the Development of Seismic Isolation Materials for Use in the Seismic Isolation Design of Underground Structures (Part 1), Joint Research Reports, Reference No. 154, Nov. 1996 (in Japanese)

2) Public Works Research Institute, et. al.: Report on Joint Research on the Development of Seismic Isolation Materials for Use in the Seismic Isolation Design of Underground Structures (Part 2), Joint Research Reports, Reference No. 192, Dec. 1997 (in Japanese)

3) Public Works Research Institute, et. al.: Report on Joint Research on the Development of Seismic Isolation Materials for Use in the Seismic Isolation Design of Underground Structures (Part 3), Underground Structure Seismic Isolation Design Manual, Joint Research Reports, Reference No. 211, Sept. 1998 (in Japanese)

4) Shigeki Unjoh, et. al.: Seismic Isolation Structures and Seismic Isolation Design of Underground Structures, Proceedings of the Sixth Tunnel Engineering Research Conference, Vol. 8, pp. 31-38, 1998 (in Japanese)

5) Public Works Research Institute: Numerical Analysis of Response Properties of Ground During Earthquakes, - DESTRA -, PWR Document No. 1778, February 1982 (in Japanese)

6) Yasuda, Yamaguchi: Dynamic Deformation Properties of Various Categories of Undisturbed Soil, Twentieth Soil Engineering Research Conference, pp.539-542, June 1985 (in Japanese)

7) Katayama Ikuo et. al.: Proposal of the "Response Seismic Coefficient Method" a Practical Quasi-dynamic Analysis Method for Structures Buried Underground, Fortieth Annual Technical Conference of the Japan Society of Civil Engineers, Part 1, pp.737-738, 1998 (in Japanese)

8) Takeyasu Suzuki et. al. Dynamic Properties of Silicon Seismic Isolation Material for Tunnel Seismic Isolation Work, Proceedings of the Thirty-second Conference on Ground Engineering, pp.2095-2096, 1997 (in Japanese)

9) Takeyasu Suzuki, et. al.: Experimental Study of Silicon Material for Urban Tunnel Seismic Isolation Structures, Collected Reports of the Japan Society of Civil Engineers, No. 534/VI-30, pp.69-76, 1996 (in Japanese)

10 Shigeki Unjoh, et. al.: Function Verification Testing of Seismic Isolation Structures for Use at Vertical Shaft Connections, Collected Papers and Reports on Tunnel Engineering Research, Vol. 9, 1999 (in Japanese)

11) Shigeki Unjoh, et. al.: Draft Manual for Seismic Isolation Design for Underground Strucutres, Proceedings of the 30th Joint Meeting on Wind and Seismic Effects, UJNR, NIST SP931, August 1998

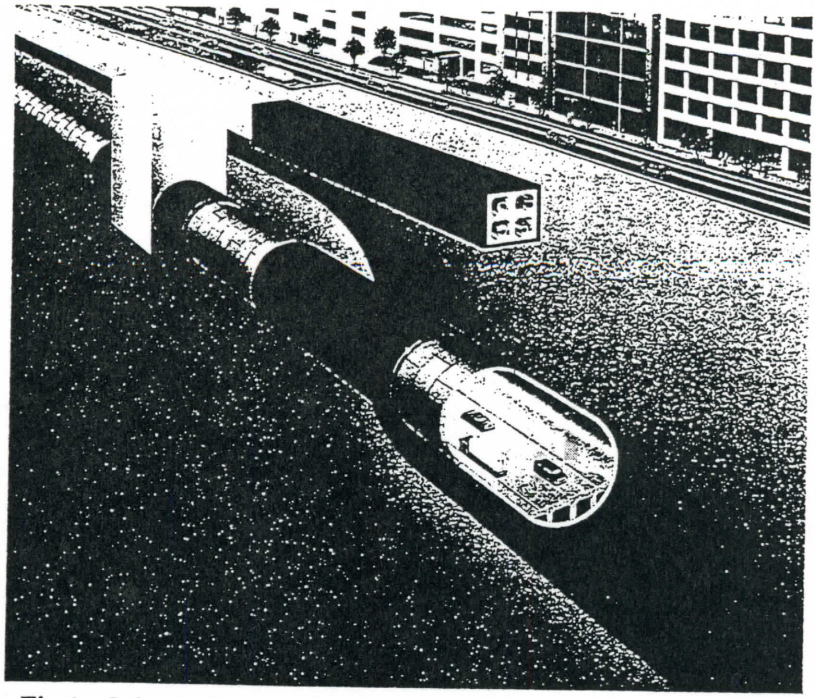


Fig.1 Seismic Isolation Technology for Underground Structures

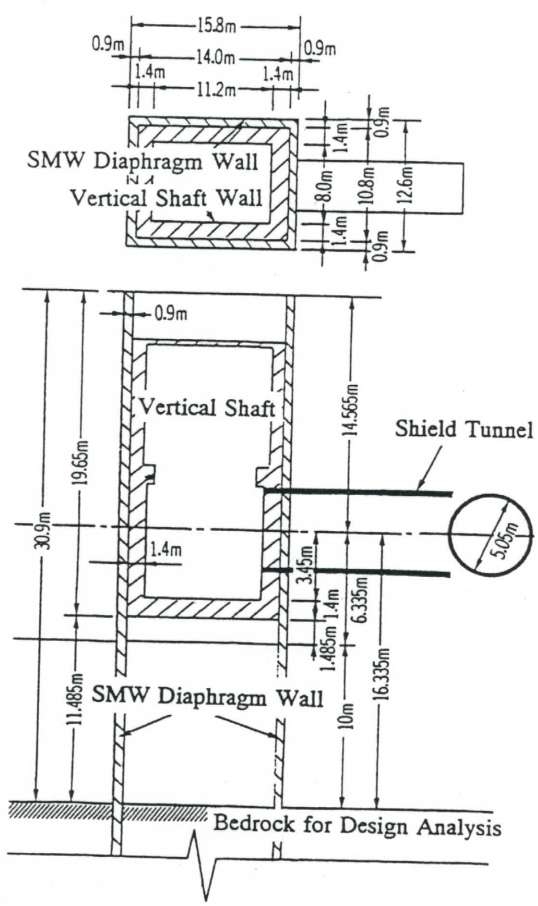


Fig.2 Layout of the Vertical Shaft and Tunnel

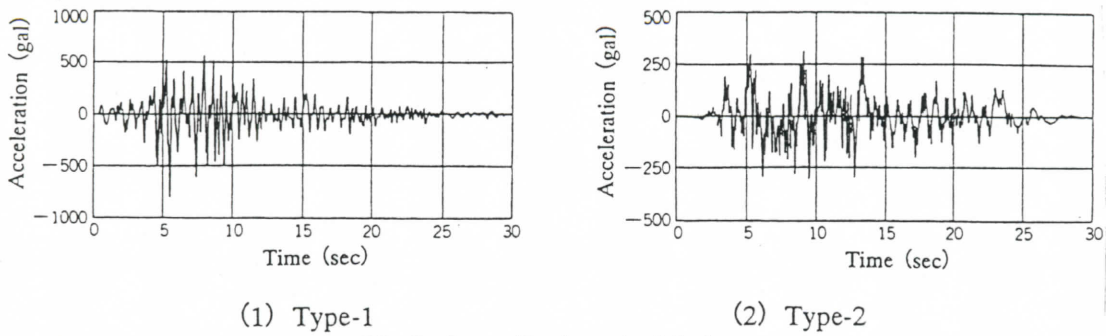


Fig.3 Input Earthquake Motion

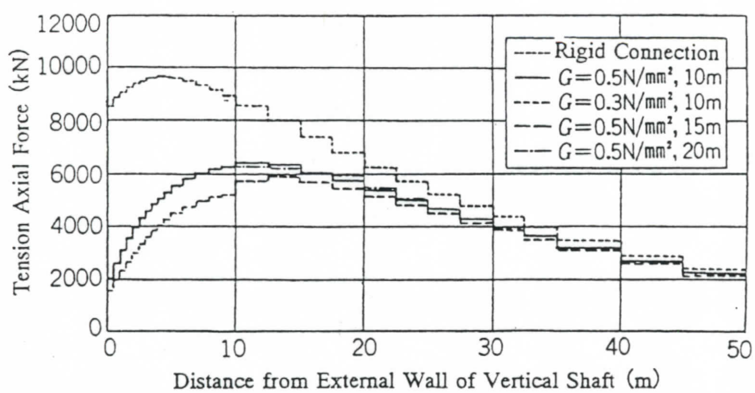


Fig.4 Effect of Shear Modulus and Length of Seismic Isolation Layer

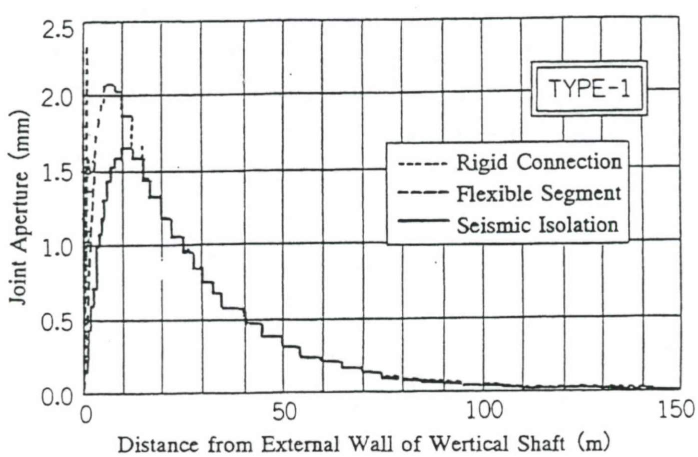


Fig.5 Analysis of Ring Joint Aperture

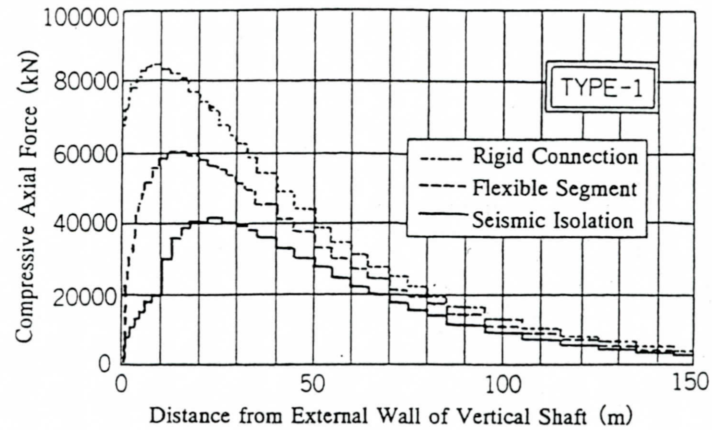


Fig.6 Analysis of Compressive Axial Force of Segments

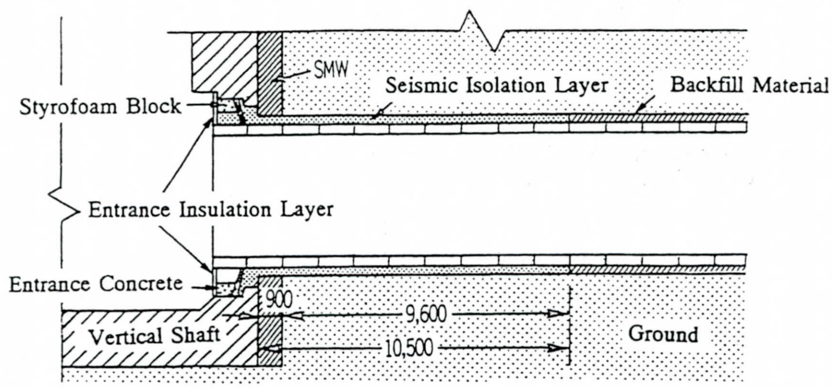


Fig.7 Seismic Isolation Structure at Start Vertical Shaft

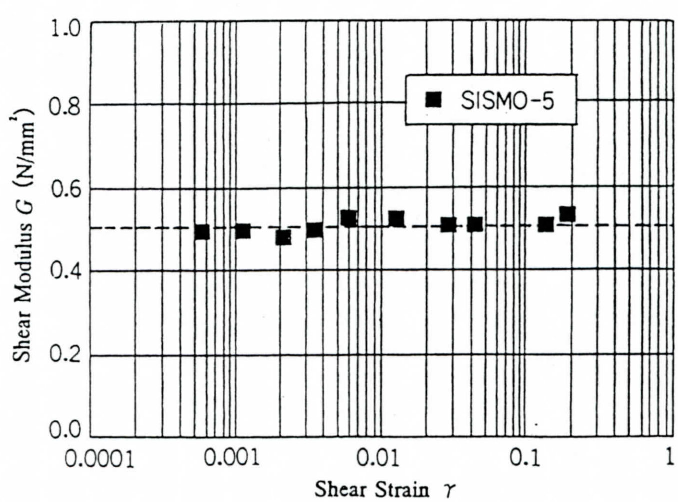


Fig.8 Strain Dependency of Shear Modulus of Silicon Seismic Isolation Material

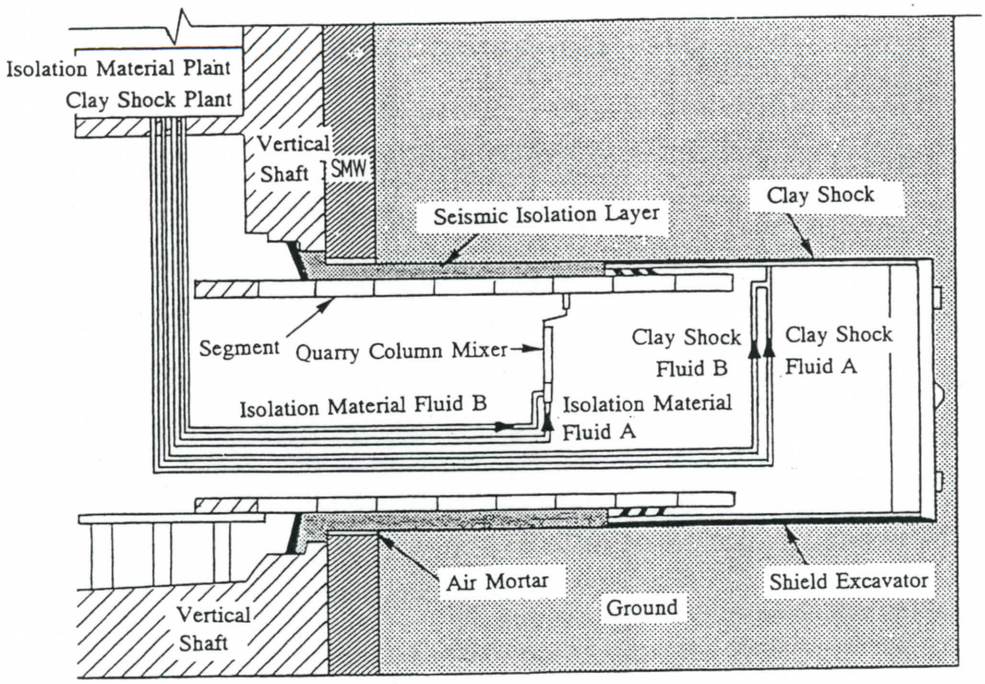


Fig.9 Silicon Seismic Isolation Material Injection

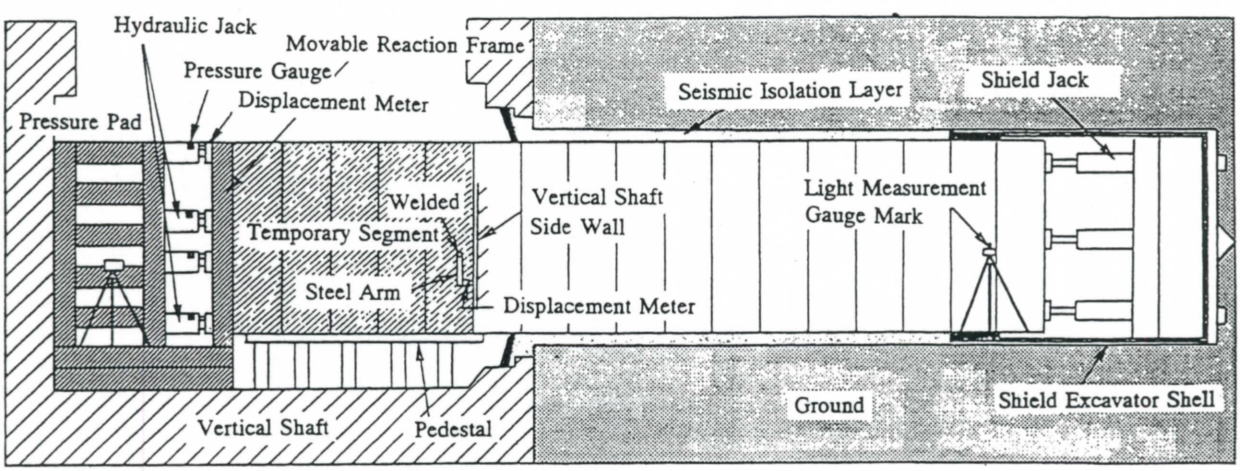


Fig.10 Schematic of Field Measurement Test

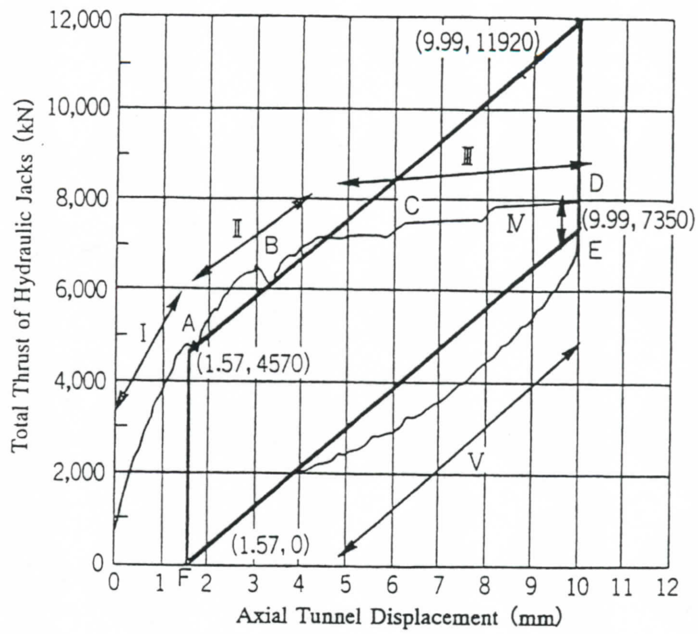


Fig.11 Jack Thrust and Axial Tunnel Displacement Relationship