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SEISMIC ISOLATION EFFECT FOR A TUNNEL WITH A SOFT ISOLATION LAYER

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This paper describes seismic isolation effects for a rectangular shape tunnel with soft seismic isolation layers installed in two different patterns: an isolation layer installed around the tunnel for a newly build tunnel and vertical isolation walls installed at both sides of an existing tunnel.

The isolation layer with shear modulus of 1/100-1/1000 of the ground can restrain propagation of shear strain during an earthquake. For the newly build tunnel, additional section forces due to an earthquake can be reduced to a half of those without isolation. For the existing tunnel, the section forces can be reduced up 40-70% of those without isolation.

Key Words: seismic isolation, earthquake, tunnel, 2D FE analysis, shear modulus

1. INTRODUCTION

Underground structures such as tunnels move together with the ground around them as long as the ground is safe against failures such as liquefaction. As a result, the section forces during an earthquake become larger as the stiffness of the structure becomes higher. Consequently, the conventional design procedures to increase the area of the section and reinforcement may not be reasonable. However, by applying seismic isolation, e.g., cutting off the transmission of ground deformation (or strain) to the structure or lowering the soil-tunnel interaction, the section forces during an earthquake can be reduced. [1), 2), 3)]

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Lately started, several researches regarding seismic isolation for underground structures have been carried out for reducing cross sectional forces of circular shape tunnels and shafts. Kawashima and Ono et al.[4), 5), 6), 7)] and Suzuki et al.[8), 9), 10), 11), 12)] conducted analytical and experimental researches of seismic isolation of tunnels and shafts in the longitudinal direction. Takeuchi and Takahashi et al.[13), 14), 15)] conducted experimental and analytical studies for circular shape tunnels in the cross-sectional direction. On the contrary, the number of researches for rectangular tunnel in the longitudinal direction is relatively few, which are the reports of analytical case studies by Ohtsuka and Hoshikuma et al.[16)] and Suzuki[17)].

Since 1995, the Public Work Research Institute, the Public Work Research Center and 17 companies including the authors have cooperated to study application of seismic isolation at the boundary of different ground types and around the tunnel-shaft joint, and

Table1 Properties of Structure

Parts	Sidewall	Center Wall	Upper Slab	Lower Slab
Density ρ	2.5			
Elastic Modulus E(MPa)	25.5×10^3			
Area A(m^2/m)	0.55	0.15	0.65	0.70
Moment of Inertia I (m^4/m)	6.932×10^{-3}	5.625×10^{-4}	1.144×10^{-2}	1.429×10^{-2}

develop the isolation materials and the technology for design and construction of shield and open-cut tunnels with the materials.[2), 18)]

In this paper, the isolation mechanisms of cross-sectional movement due to earthquakes for newly-built rectangular shape tunnel, of which the authors have been in charge in the research project, are introduced and the influences of properties and arrangement of isolation layers on the isolation effects are described. In addition, construction of soft walls at the both side of a tunnel is suggested as seismic isolation for existing rectangular shape tunnel and the influences of depth, location and thickness of the soft layers on the isolation effects are documented.

In this study, linear analysis with inertia force equivalent to seismic displacement[2), 19)], i.e. 2D FE analysis applying horizontal inertia force equivalent to the first mode deflection of the ground, was conducted.

2. ANALYSIS WITH INERTIA FORCE EQUIVALENT TO SEISMIC DISPLACEMENT

(1) Procedures

The first mode deflection U_h of the homogeneous ground is given with the parameters t, time, and z, depth from the surface as the following equation.

$$U_h(z,t) = U_{h0}\cdot\cos(\frac{\pi z}{2H})\cdot\sin(\frac{2\pi t}{T_s}) \qquad (1)$$

where H and T_S are the thickness and period of the ground, respectively. U_{h0} is the maximum displacement at the ground surface, which can be determined from the period of the ground T_S and the maximum response velocity S_V based on the following equation (Japan Road Association, 1986[20)]).

$$U_{h0} = \frac{2}{\pi^2}\cdot S_v\cdot T_s \qquad (2)$$

The horizontal acceleration of the ground, at the moment when the maximum displacement occurs, is obtained by differentiating the equation (1) with t and substituting the equation (2) for U_{h0} as follows.

$$\alpha(z) = -\frac{8\cdot S_v}{T_s}\cos(\frac{\pi z}{2H}) \qquad (3)$$

In this study, a horizontal inertia force corresponding to the response acceleration was applied as a body force on each element for the ground, tunnel lining and soft layers. The resultant section forces in the tunnel lining correspond to the additional section forces due to an earthquake. In the following description, analysis with these procedures is called as analysis with equivalent inertia force.

(2) Applicability of analysis with equivalent inertia force

In this chapter, the applicability of analysis with equivalent inertia force was verified by comparing with the results from dynamic 2D FE analysis. The tunnel for the analysis was a RC twin-box type, whose cross section and properties are shown in **Fig. 1** and **Table 1**, respectively. In order to take cracks into account, the moment of inertia shown in **Table 1** was reduced to the half of that for the whole cross-section. The model ground had 30m of thickness and properties shown in **Table 2** were used for the analysis.

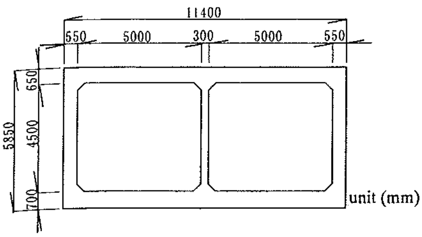


Fig.1 Cross Section of Rectangular Tunnel

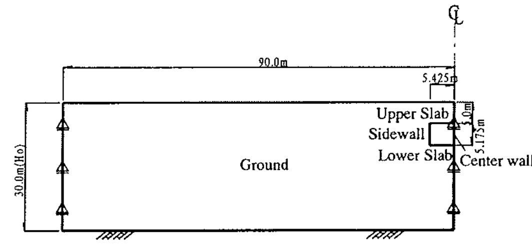


Fig.2 Model for 2D FE Analysis

Table2 Proberties of Ground

Thickness of Ground Ho (m)	30
Shear Wave Velocity Vs (m/sec)	115
Natural Period Ts (sec)	1.043
Maximum Response Velocity S_V (m/sec)	0.24
Dencity ρ	1.6
Shear Modulus Gg (MPa)	21.2
Poisson's Ratio ν g	0.49

Table3 Reduction Ratios of Section Forces

		Dynamaic 2D FE Analysis	Analysis With Equivalant Inertia Force
Side Wall	M/M_o	0.65	0.64
	Q/Q_o	0.35	0.46
	N/N_o	0.38	0.39
Center Wall	M/M_o	0.83	0.84
	Q/Q_o	0.85	0.86

M/M_o:Reduction Ratio of Bending Moment
Q/Q_o:Reduction Ratio of Shear Force
N/N_o:Reduction Ratio of Axial Force

Table4 Proberties of Ground

	Soft Ground	Hard Ground
Thickness of Ground Ho (m)	30	30
Shear Wave Velocity Vs (m/sec)	115	174
Natural Period Ts (sec)	1.043	0.690
Maximum Response Velocity S_V (m/sec)	0.24	0.24
Dencity ρ	1.6	1.8
Shear Modulus Gg (MPa)	21.2	54.5
Poisson's Ratio ν g	0.49	0.45

For dynamic cases, response history analysis with modal procedures was conducted by inputting the standard design earthquake motion for the ground type I in the reference by Japan Road Association (1990) at the base of the model shown in **Fig. 2.** In the cases with equivalent inertia force to seismic displacement, static analysis with the analytical model shown in **Fig. 2** was conducted by applying horizontal inertia forces obtained from Equation (3).

Table 3 shows the ratio of the maximum section forces of the tunnel with seismic isolation to those of the tunnel without seismic isolation (this ratio is called as reduction ratio of section force in the description below) from the result of the dynamic 2D FE analysis and the reduction ratio of section force from the result of the analysis with equivalent inertia force. The properties of the isolation layer were thickness of 10cm, shear modulus of 1/100 of that of the ground, specific gravity of 1.0 and Poisson's ratio of 0.49 and the isolation layer was located around the tunnel as shown in **Fig. 3.**

As shown in **Table 3**, the result from the analysis with equivalent inertia force agreed precisely with that from the dynamic analysis. Consequently, for the case that the first mode dominates the deflection shape, the analysis with equivalent inertia force is effective and trustful.

3. PARAMETRIC STUDY FOR SECTION FORCE DUE TO EARTHQUAKES

(1) Tunnel and Ground

The structure of the tunnel in this study was twin RC box shape as shown in **Fig. 1** and its properties are shown in **Table 1.** Two types of the ground around the tunnel, soft and hard ground, were considered for this study and the surface ground of the both types was 30m thick and homogeneous. The properties of the ground are shown in **Table 4 .**

(2) Analytical Model

In this study, the area for the analysis is horizontally 90m from the center of the tunnel and symmetry of the model was considered as shown in Fig. 2. The ground and isolation layer were modeled into iso-parametric plane strain elements and the

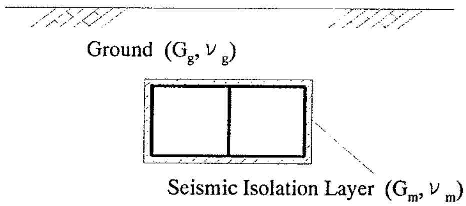


Fig.3 Seismic Isolation for Newly-Built Tunnel

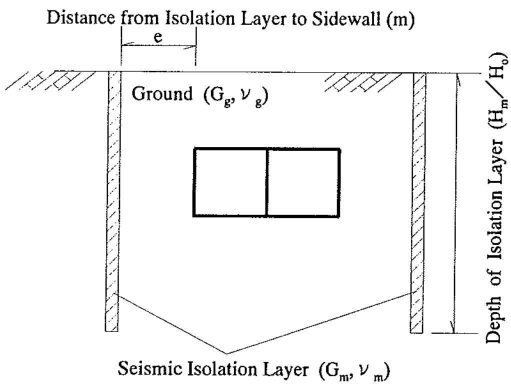


Fig.4 Seismic Isolation for Existing Tunnel

tunnel members were modeled into 2D beam elements. The axis lines of the beam elements were located on the geometric center of the members without taking haunches into account. The haunch parts were not differentiated. Vertical displacement at the side boundaries and horizontal and vertical displacement at the bottom boundary were fixed in this analytical model.

(3) Parameters and Cases for Analysis

The two types of arrangements of isolation layers were analyzed in this study. In Cases 1-9, isolation layers were installed around a newly built tunnel as shown in **Fig. 3**. In Cases 10-21, isolation layers were vertically installed near the both sides of an existing tunnel as shown in **Fig. 4**. **Tables 5** and **6** compare the parameters and the cases for the analysis.

As shown in **Table 5**, the analysis for a newly built tunnel, Cases 1-9, was conducted with parameters such as properties of isolation layers (shear modulus G_m and Poisson's ratio ν_m) and the arrangements of isolation in two types of model ground, hard and soft ground. 'G_m/G_g' in the table stands for the ratio of shear modulus of the isolation layer G_m to that of the ground around G_g. 'Sides', 'Top & Sides' and 'All' in the arrangement columns in the table stand for installation of isolation layers on both sides of the tunnel, on the upper slab and both sides, and on the upper and lower slabs and both sides, respectively.

As shown in **Table 6**, the analysis for an existing tunnel, Cases 10-21, was conducted for 10cm and 30cm thick of isolation layers with parameters such as the depth of isolation layers and distance from the side walls in the soft ground. The shear modulus ratio G_m/G_g and the Poisson's ratio were fixed for 0.01 and 0.49, respectively.

Case 0 in **Tables 5** and **6** stands for the case without isolation layers and the Poisson's ratio and density of the isolation layers were identical to the ground around.

4. SEISMIC ISOLATION AND ITS EFFECT FOR NEWLY BUILT TUNNEL

(1) Performance during Earthquake and Effect of Isolation Layers

In this section, the performance of a newly built tunnel during earthquakes by comparing the results of Cases 0 and 6 is described.

Fig. 5 on the left-hand side compares the seismic section forces of the tunnel with isolation layer to that of the tunnel without isolation layers. Solid and broken lines show the results of Case 0 without isolation layers and Case 6 with isolation layers, respectively. The numbers and solid circle show the maximum values and their locations.

In Case 0 without isolation layers, relatively large absolute values of all section forces occurred at joints between slabs and sidewalls, compared to those at the middle of these members. Along the sidewall, larger section forces occurred at the joint with the lower slab compared to those at the joint with the upper slab. Along the center wall, larger bending moment occurred at the joint with the lower slab compared to those at the joint

Table5 Title Case for Newly-Built Tunnel

Cases of Analyses	Shear Modulus of Isolation Layer (G_m/G_g)				Poisson's Ratio of Isolation Layer (ν_m)			Layer Arrangement			Remarks
	1.0	0.1	0.01	0.001	0.1	0.3	0.49	Sides	Top & Sides	All	
CASE0	○									○	Without Isolation Layer
CASE1		○				○				○	Effect of Shear Modulus
CASE2			○			○				○	
CASE3				○		○				○	
CASE4			○		○					○	Effect of Poisson's Ratio
CASE5			○			○				○	
CASE6			○				○			○	
CASE7			○			○		○			Layer Arrangement
CASE8			○			○			○		
CASE9			○			○				○	

Table6 Title Case for Existing Tunnel

Cases of Analyses	Depth of Layer/Ground (30m) (H_m/H_o)						Distance from Layer to Sidewall e (m)						Remarks
	0.17	0.34	0.51	0.67	0.83	1.00	0.0	1.0	2.0	3.0	5.0	10.0	
CASE0													Without Isolation Layer
CASE10	○							○					Effect of Depth of layer
CASE11		○						○					
CASE12			○					○					
CASE13				○				○					
CASE14					○			○					
CASE15						○		○					
CASE16				○			○						Effect of Distance from Layer to Side Wall
CASE17				○				○					
CASE18				○					○				
CASE19				○						○			
CASE20				○							○		
CASE21				○								○	

with the upper slab while larger shear force occurred at its lower part. No axial force occurred along the center wall, in this condition.

In Case 6 with isolation layers, the distribution of section forces was averaged and the maximum values were reduced compared to the case without isolation layers, especially for the shear forces. Along the sidewalls and slabs, the section forces near these joints decreased drastically. Along the center wall, on the other hand, drastic change did not occur.

The section forces due to earthquake in the direction of perpendicular to the tunnel axis can be divided into three components: 1) section forces due to deformation of the free field, 2) due to shear force on the tunnel surface and 3) due to inertia force of the tunnel (Kawashima et al.[21], 1994). By dividing the section force into these three components as follows, the isolation mechanism for the tunnel is clarified in this section.

1) Section force due to deformation of the free field

This component of the section force is obtained by subtracting the second and third components from the section force.

2) Section force due to shear force on the tunnel surface

This component is obtained by inputting the shear stress of the free field on the tunnel-lining surface. The shear stress of the free field is obtained by differentiating the displacement distribution in the equation (1) by depth z and substituting the equation (2) and represented by the following equation.

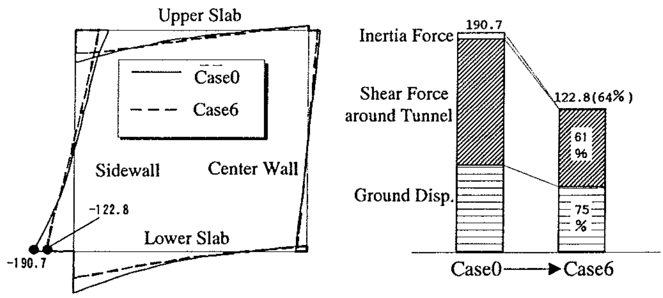
$$\tau(z) = \frac{G_g}{\pi H} \cdot S_V \cdot T_S \cdot \sin\left(\frac{\pi z}{2H}\right) \qquad (4)$$

where τ_z is the shear stress at the depth z and G_g is the shear modulus of the ground.

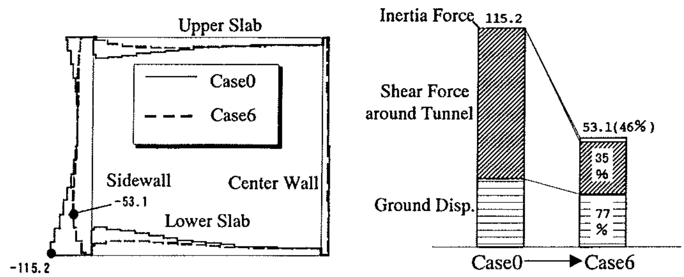
3) Section force due to inertia force of the tunnel

This component is obtained by inputting the horizontal inertia force in the tunnel lining which was calculated from the equation (3).

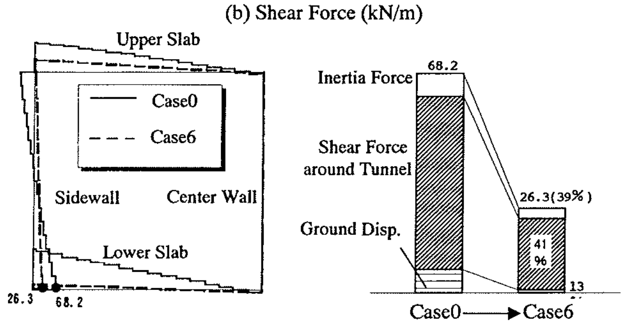
Fig. 5 also schematically shows the ratios of these components to the maximum section forces in the sidewall and the reduction effect



(a) Bending Moment (kN·m/m)

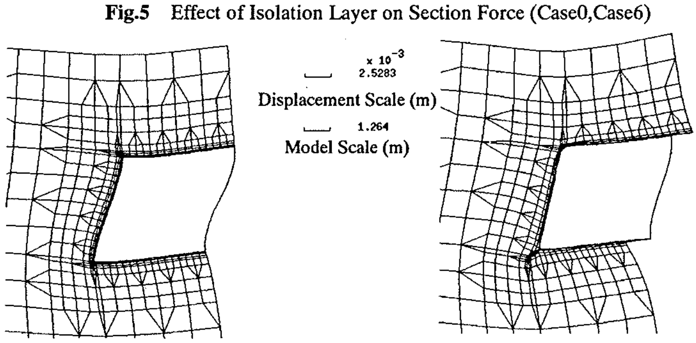


(b) Shear Force (kN/m)



(c) Axial Force (kN/m)

Fig.5 Effect of Isolation Layer on Section Force (Case0,Case6)



(a) Without Isolation Layer(Case0)

(b) With Isolation Layer (Case6)

Fig.6 Displacement around Tunnel for Shear Force

of the isolation layer. The percentages in the column graphs show the reduction rates of the components due to deformation of the free field and due to shear force on the tunnel surface and the numbers in parentheses are the reduction rates for the maximum section forces. Because the maximum shear forces occurred at the different locations in Cases 0 and 6, the reduction rates for the shear force are based on the results from different locations. The percentage of the component due to shear force to the maximum section

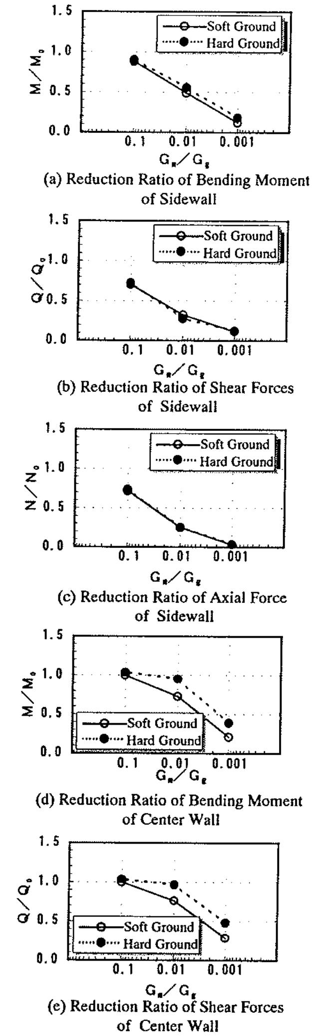


Fig.7 Effect of Shear Modulus of Isolation Layer on Section Forces (ν_m=0.3)

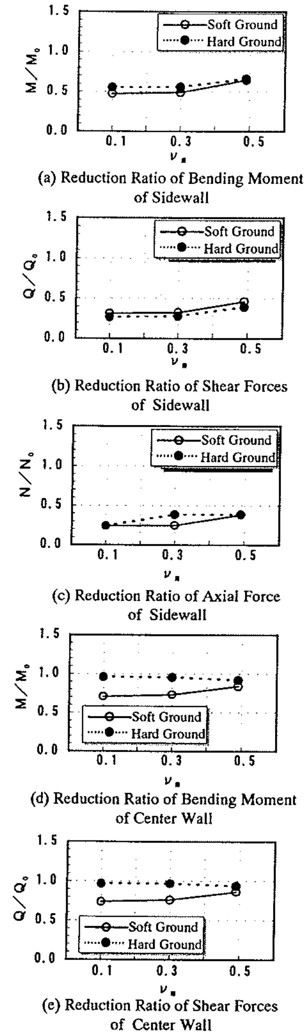


Fig.8 Effect of Poisson's Ratio of Isolation Layer on Section Forces (G_m/G_g=0.01)

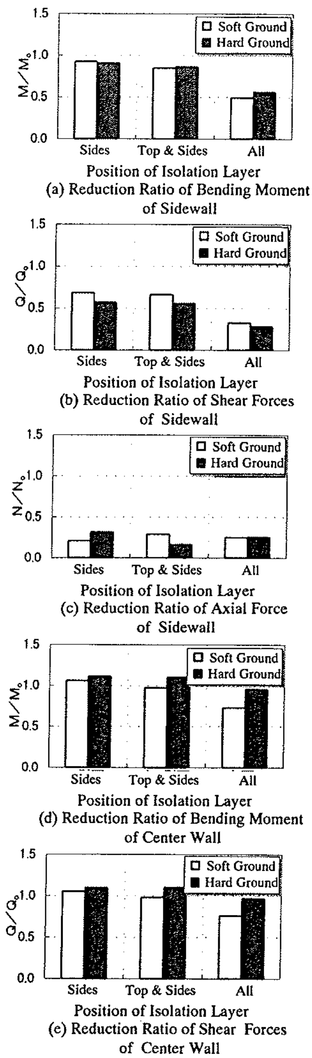
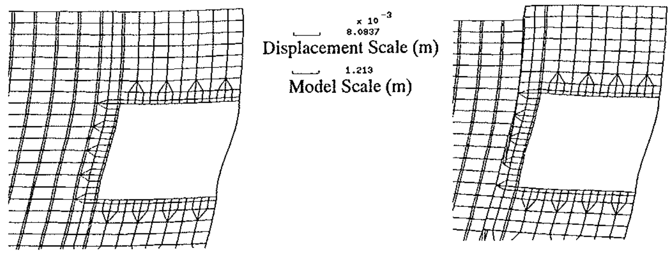


Fig.9 Effect of Positoin of Isolation Layer on Section Forces (G_m/G_g=0.01, ν_m=0.3)

forces was the largest and 60-80% in the case without isolation layers. The percentage of the component due to deformation of the free field was the second largest and that due to inertia force was small and less than 10%. As shown in this figure, the isolation layer reduced the component due to shear force to 40-60% and the component due to deformation of the free field to 75%. Consequently, the maximum section forces were reduced to 40-60%.

Fig. 6 shows the deflection shape of the tunnel based on the results from analysis with the shear force on the tunnel surface, which caused the largest influences on the section force. The lateral relative displacements between the upper and lower slabs without and with isolation are 2.8mm and 2.0mm and the installation of the isolation layer resulted in reduction of relative displacement to 70%. On the contrary, the deformation of the ground around the tunnel increased in the case with the isolation layer. Thus, the isolation layer with low rigidity largely deforms and the interaction between the ground and tunnel is decreased, with the result that shear deformation of the tunnel can be reduced.



(a) Without Isolation Layer(Case0) (b) With Isolation Layer (Case15)

Fig.11 Displacement around Tunnel

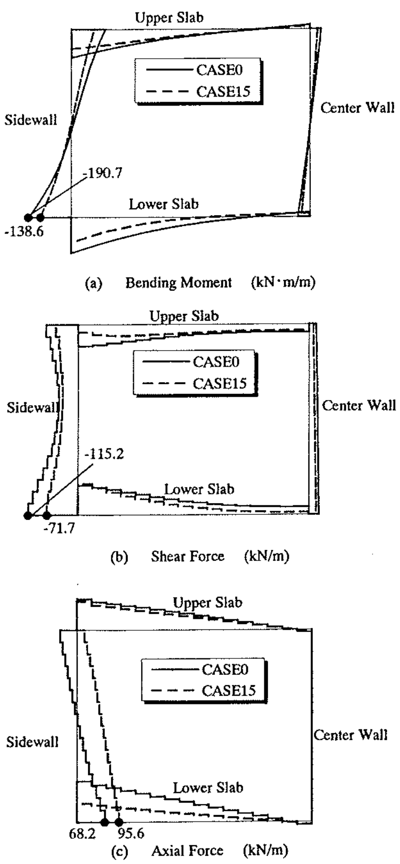


Fig.10 Effect of Isolation Layer As Vertical Walls on Section Forces

(2) Effect of Properties of Isolation Layer

Fig. 7 summarizes the effects of the rigidity ratio G_m/G_g on the section force in the side and center walls (Cases 1, 2 and 3). The Poisson's ratios in these cases were 0.3. The solid and broken lines show the cases with the soft and hard ground, respectively. M/M_0, Q/Q_0 and N/N_0 on y-axes in these graphs show the reduction factors of the maximum bending moment, shear force and axial force. As shown in the figure, the reduction factors of the bending moment, shear force and axial force in the sidewall were 0.5, 0.3, and 0.25 respectively for the case with G/G_0 of 0.01 and 0.15, 0.1 and 0.05 respectively for the case with G/G_0 of 0.001. On the contrary, the reduction factors of the bending moment and shear force in the center wall were 0.95-0.75 for the case with G/G_0 of 0.01 and 0.4-0.2 for the case with G/G_0 of 0.001. Thus, the shear modulus ratio of the isolation layer largely influenced the maximum section forces; the section forces were reduced more drastically for smaller shear modulus ratio. as the shear modulus. This tendency is more remarkable for the sidewall than for the center wall.

As also shown in this figure, the reduction factor for the soft ground was about the same as that for the hard ground, except for the center wall in the case with G/G_0 of 0.01, which resulted in 20% smaller reduction factor for the soft ground than the hard ground. Therefore, with the same shear modulus ratios, the effect of the differences in the shear modulus of the ground on the reduction factor is small.

Similarly, Fig. 8 summarizes the effects of Poisson's ratio on the section force in the side and center walls (Cases 4, 5 and 6). The rigidity ratios G_m/G_g in these cases were 0.01. As shown in this figure, the effects of Poisson's ratio were not significant although the case with larger Poisson's ratio near 0.5 of the isolation layer resulted in larger reduction factor of section force.

(3) Arrangement of Isolation Layers

Fig. 9 summarizes the effects of arrangements of isolation layers with its rigidity ratio of 0.01 on the section forces in the sidewall and center wall (Cases 7, 8 and 9). The open and solid bars in the graphs show the cases with the soft ground and hard ground, respectively. The horizontal lines show the arrangements of isolation layers; 'Sides', 'Top & Sides' and 'All' show the cases with isolation layers on the both sidewalls, on the upper slab and both sidewalls, and on the upper and lower slabs and both sidewalls, respectively.

The case with larger installation area of isolation layers resulted in smaller bending moment and shear forces in the sidewall and those in the case with isolation layers all around the tunnel were reduced to about a half of those in the case with isolation layers on the both sidewalls. On the contrary, the reduction factors of the center walls were almost constant except for the case with all around the tunnel. Therefore, it is necessary to install isolation layers all around a tunnel for reducing bending moment and shear forces in the center wall. The reduction factor of axial forces in the sidewall was less influenced by the arrangement of isolation layers than that of bending moment or shear force. It is because the axial forces in the sidewall can be reduced effectively enough only by the isolation layer on the sidewall.

5. SEISMIC ISOLATION AND ITS EFFECT FOR EXISTING TUNNEL

(1) Performance during Earthquake and Effect of Isolation Layers

In this section, the performance of an existing tunnel during earthquakes is described by comparing the results of Cases 0 and 15.

Fig. 10 compares the seismic section forces of the tunnel with isolation layers (Case 15) to that of the tunnel without isolation layers (Case 0). Solid and broken lines show the results of Case 0 without isolation layers and Case 15 with isolation layers, respectively. The numbers and solid circle show the maximum values and their locations. **Fig. 11** shows the deflection shapes at the moment when the maximum section force occurred.

In Case 15 with isolation layers, the distributions of bending moment and shear force were averaged and the maximum values were reduced compared to the case without isolation layers, similarly to Case 6. However, larger axial force in the sidewall occurred in the case with isolation layers than without them, and reduction factor of axial force in the upper and lower slabs were smaller than Case 6. This is because the interaction between the grounds inside and outside of the vertical isolation walls was reduced and the vertical deformation in the inside ground was increased, then the rotation of the tunnel was induced.

(2) Effects of Depth of Isolation Layers

Fig. 12 compares the effect of the depth of isolation layers on the maximum section forces from the results of Cases 10-15. The solid and broken lines show the case with 10cm and 30cm thick isolation layers, respectively. The distance between the isolation layers and sidewall was 1.0m. The vertical and horizontal axes show the ratio of the length of vertical isolation layers to the depth of surface ground (30m), H_m/H_0, and the reduction factors of section forces, M/M_0, Q/Q_0, and N/N_0, respectively

The smaller bending moment and shear force occurred in the case with deeper isolation layers. In the case with deeper vertical isolation layers than the depth of the lower slab (H_m/H_0=0.67), the effect of isolation on the section forces were prominent. This effect was more remarkable for thicker isolation layers, although shallower isolation layers than the depth of the lower slab (H_m/H_0=0.34) made only slight effect on the section forces.

On the other hand, the minimum axial force occurred in the case with medium length of the vertical isolation layers (H_m/H_0=0.50) and the longer isolation layers resulted in larger axial force.

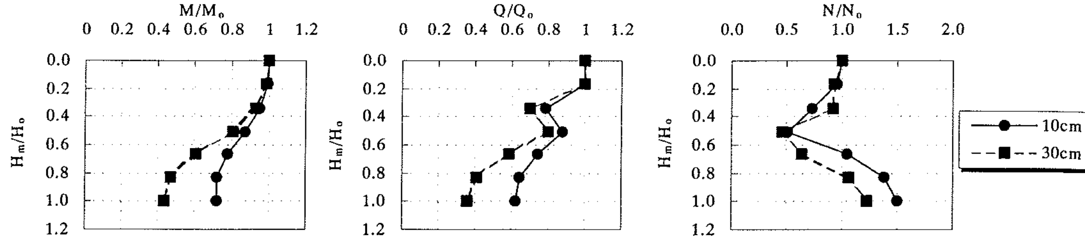


Fig.12 Effect of Depth of Isolation Layer on Section Forces

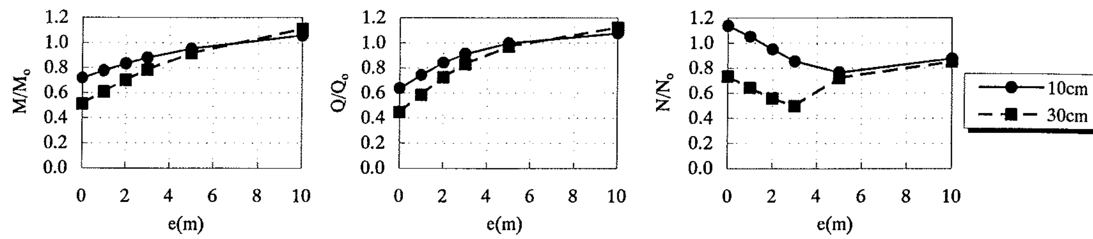


Fig.13 Effect of Distance of Isolation Layer on Section Forces

(3) Effect of Distance between Isolation and Tunnel

Fig. 13 compares the effect of the distance of isolation layers to the sidewall on the maximum section forces from the results of Cases 16-21. The solid and broken lines show the case with 10cm and 30cm thick isolation layers, respectively. The isolation layers were installed from the ground surface to -20m GL (H_m/H_0=0.67). The vertical and horizontal axes show the distance to the isolation layers, and the reduction factors of section forces, M/M_0, Q/Q_0, and N/N_0, respectively.

Smaller bending moment and shear force occurred in the cases with small distance between the sidewall and isolation layers while the isolation layers installed at the distance of more than 5m from the sidewall made slight difference in section forces. Among the cases with the isolation layers installed at the distance of less than 5m, thicker isolation layers installed at smaller distance from the sidewall reduced the section force more efficiently.

The smallest axial force occurred in the case with isolation layers installed at the distance of 3-5m and the isolation layers installed at the smaller distance resulted in larger axial force.

6. SUMMERY

In this study, isolation effects on the section forces of a rectangular tunnel caused by an earthquake were investigated by analysis with equivalent inertia force to seismic displacement with isolation layers installed on the sidewall and slabs and with vertical isolation walls installed at the both sides of tunnels. The results from this study are summarized as follows,

(1) Isolation layers, which absorb the ground strain, averaged the distribution of section forces and reduced the maximum values. Among the components of the maximum section force caused by an earthquake (the components due to deformation of the free field, due to shear force on the tunnel surface and due to inertia force of the tunnel), the component due to shear force which predominate the section force was reduced most efficiently by the isolation layer.

(2) Isolation layers of smaller shear modulus ratio (G_m/G_g) were more efficient on reduction of the section forces although difference in Poisson's ratio resulted in slight difference in the section forces. In this study, the section forces in the sidewall were reduced to less

than a half of them in the case with shear modulus ratio of 0.01, while those in the center wall were reduced to 3/4 of them.

(3) Section forces were reduced more efficiently in the case with isolation layers installed all around the tunnel than in the case with partial installation. Axial force in a tunnel member was reduced mainly by installing an isolation layer along the member.

(4) In the cases with vertical isolation wall installed at both side of an existing tunnel, the isolation layer installed at the depth of twice of the lower slab and near to the sidewalls reduced bending moment and shear force effectively. The isolation layer installed at the depth of the lower slab and the one installed at the distance of the height of the tunnel (approx. 5 m) were not effective to reduce the section forces. In the cases with 10cm and 30 cm thick vertical isolation layers installed at the distance of 1.0m from the sidewall and at the depth of 20m from the ground surface, the bending moment and shear force were reduced to 60-70% and 40-50% of the case without isolation layers, respectively.

In this study, it is clarified that the isolation layer with the shear modulus of 1/100-1/1000 of the ground can effectively reduce the section force of a tunnel caused by an earthquake in the direction of perpendicular to the tunnel axis to about a half. However, the problems regarding to cost, such as the balance between the cost for installing isolation layers and the benefit by installing the isolation layers, are remained. In the near future, the investigation for those problems including installation methods will be conducted for realization of isolation design for underground structure.

Lastly, we acknowledge that this paper is to document the achievement in 1995 of the research "development of isolation materials for isolation design for underground structure" conducted by PWRI, Civil Engineering Research Center and 17 corporations and thanks go to the research members for their effort.

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