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DAMAGES OF URBAN TUNNELS DUE TO THE SOUTHERN HYOGO EARTHQUAKE OF JANUARY 17, 1995 AND THE EVALUATION OF SEISMIC ISOLATION EFFECT

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ABSTRACT

A subway station was collapsed due to the southern Hyogo earthquake of January 17, 1995. This paper presents a typical damage of a subway tunnel due to this quake and introduces two different seismic isolation methods effective to highly improve seismic safety of underground structures. Earthquake response simulations are carried out, modeling the most severely damaged subway station, in order to detect the major cause of the damage. The simulation indicates that the damage would be mainly originated from the horizontal earthquake motion. Earthquake response analyses are also carried out, applying two seismic isolation methods to the subway station model. Then, the effectiveness and the validity of these methods are exhibited.

KEYWORDS

Earthquake damage; Urban tunnels; Numerical simulation; Seismic isolation method; Effect evaluation

INTRODUCTION

In the morning of January 17, 1995, a terrible earthquake motion hit the Hanshin area of Japan, centering at Kobe city. One of the subway stations in Kobe city completely collapsed and several kilometers of the general tunnel section and several other subway stations were more or less damaged by this earthquake. Even though the underground sewer tunnel in Mexico city was damaged due to the Michoacan earthquake of 1985 (Tamura *et al.*, 1986), it was not a destructive one. The collapse of the subway station in Kobe city was the first severe damage that subways have ever experienced.

It is true that underground structures are safer than ground facilities. This damage indicates, however, that a destructive case may possibly occur when an earthquake ground motion stronger than we have never estimated strikes a lifeline. The safety of important underground lifelines which must fulfil its function in emergency should be maintained even if a large earthquake occurred.

The author have proposed the seismic isolation system for urban tunnels (Suzuki, 1990), in which the tunnel structure is covered by a thin soft isolation layer. Several functions of the seismic isolation layer are clarified through numerical analyses as well as verification tests using a shaking table. In this paper, another method for seismic isolation for underground tunnels is presented, in which a seismic isolation rubber with no damping is fixed between a ceiling slab and a center column for a tunnel with a rectangular cross-section.

In this paper, a typical damage of subway stations due to the southern Hyogo earthquake of January 17, 1995 are demonstrated first. Then, the main cause of the damage is deduced by numerical simulations, modeling the damaged station. Next, the two seismic isolation methods are applied to the tunnel model and numerical simulations are carried out. Then, the effectiveness and necessity of the application of seismic isolation methods to underground structures are discussed.

DAMAGES OF SUBWAY TUNNELS

Subways in Kobe city and generals of damages in subway tunnels

There are two subway lines in Kobe city. One is the Kobe city subway runs in the northern part of the city. Another is the Kobe express railway which runs in the southern part. They cross each other at Nagata. The former was constructed around 1980, the latter was in 1960s. Both of the subway lines were constructed by means of the open-cut-method and the shape of a tunnel cross-section is rectangular with columns at the center of a tunnel. Fig.1 illustrates main transportation lines in Kobe city including subway lines.

Earthquake damages occurred in both subway lines, covering a few kilometers in length. One of the typical damages is the shear collapse of center columns, especially at station platforms with wide width. Collapses of center columns are also seen in the general tunnel section, where the width of the tunnel is shorter than that at stations. Longitudinal cracks were seen on side walls and transverse cracks are seen both on a floor slab and on a ceiling slab as well as on side walls in general tunnel section. The severest damage occurred at the Daikai station is briefly summarized in the following paragraph.

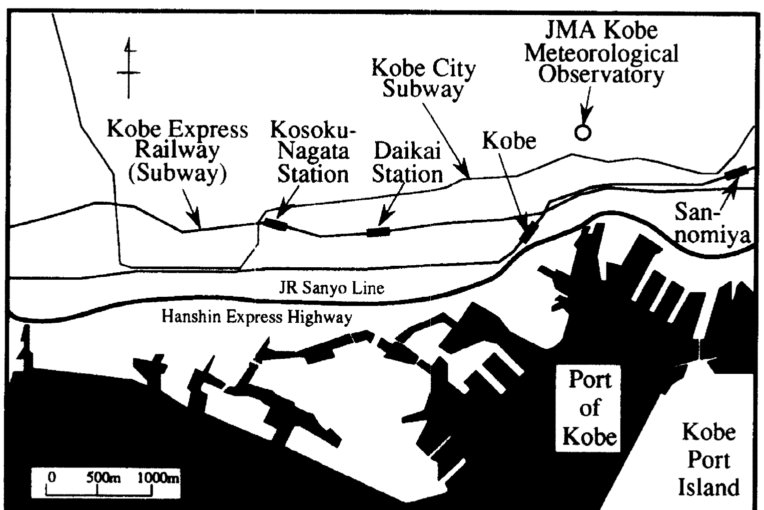


Fig.1 Main transportation lines in the western part of Kobe city

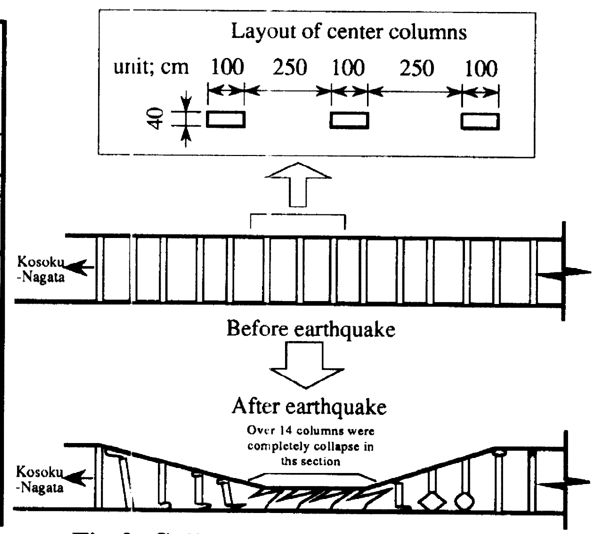


Fig.2 Collapse at the Daikai Station

Damages occurred at a subway station

The severest damage occurred at the Daikai station, the location of which is pointed out in Fig.1. At this station, over 14 center columns were completely collapsed and the ceiling slab bent down to the floor slab. On the ground surface right over the collapsed portion, a large subsidence with almost 80 m in length, 20 m in width, and 1 m in depth at maximum, took place as shown in Photo.1.

Fig.2 illustrates the schematic representation of the damage occurred at the platform. The collapse of center columns are mainly classified into the following three patterns. Photo.2 shows the first collapse pattern, i.e., complete collapse. In this pattern, columns with a cross-section of 1 m by 0.4 m are completely collapsed and main reinforcement bars are bent out to whichever northern or southern side. Photo.3 shows the second pattern in which collapse due to shear force took place at the bottom or the top of columns. Photo.4 shows the third pattern, on the contrary, in which columns are buckled at the bottom or the top subjected to the axial force. Judging from the distribution of each pattern of collapse illustrated in Fig.2, the main cause of the damage can be estimated as follows:


Photo.1 Subsidence of the pavement occurred over the subway station

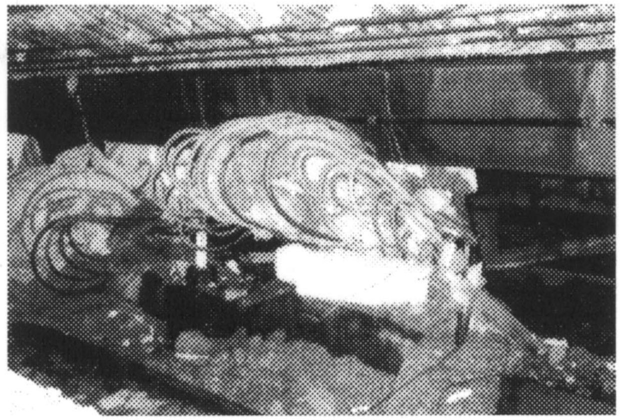


Photo.2 Complete collapse of center columns (the first pattern of collapse)

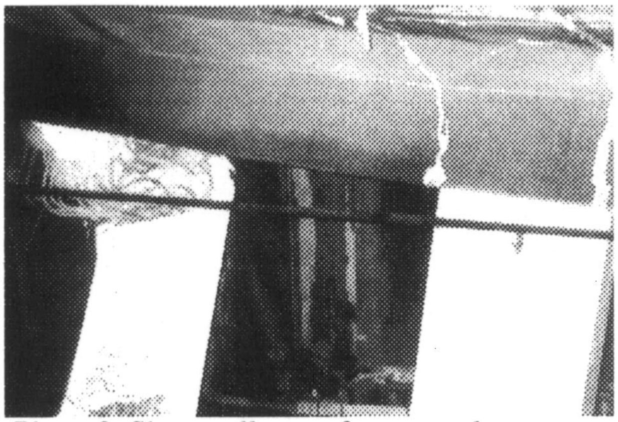


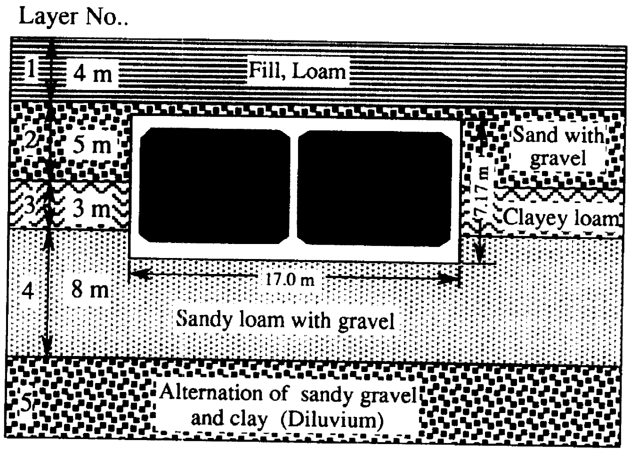
Photo.3 Shear collapse of center columns (the second pattern of collapse)


Photo.4 Buckling of center columns (the third pattern of collapse)

In the first step, a large relative displacement is provoked due to the strong horizontal ground motion and shear cracks of center columns take place at the bottom and the top of columns. Cracks due to the bending moment are developed on side walls as well originated from the shear deformation of the tunnel cross-section, which accelerates the collapse of center columns. The second collapse pattern appears in this step. Generally speaking, center columns support the heavy earth pressure by their axial force, the axial force of which is much higher than that supported by side walls in the tunnel cross-section with a large width like this station. Due to a lack of support by center columns, the downward deformation of the ceiling slab is accelerated and the cracks take place there. The soil covering the tunnel also deforms in company with the slab deformation. Then, the tensile crack penetrating from the tunnel to the ground surface developed, which can be clearly seen in Photo.1. The ceiling slab collapses and drops down to the floor slab, crashing center columns as shown in Photo.2. Large axial force having been supported by a sound center column shifted to the neighboring column successively, which forces the column being buckled in a form classified into the third collapse pattern represented by Photo.4.

NUMERICAL SIMULATIONS OF THE DAMAGED SUBWAY STATION

Earthquake response analyses of the damaged subway tunnel were conducted, in order to detect the main cause of the damage. In the analyses, the cross-section of the subway station and surface soil deposits were modeled roughly using 2-dimensional linear finite elements. The profile and dynamic properties of soil deposits used in the analyses are shown in Fig.3 as well as the location of the subway station. They are given from the logging data conducted near the subway station (Geological Survey of Japan, 1983). The soil is replaced by quadrilateral or triangular plane elements and the tunnel is replaced by beam elements with unit depth, respectively. The dimensions in thickness for a ceiling slab, a floor slab and side walls are 0.8 m, 0.85 m and 0.7 m, respectively. Since RC-center columns with a cross-section of 1 m by 0.4 m are arranged in an interval of 3.5 m in the tunnel axial direction as shown in Fig.2, the stiffness of beam elements for a center column is determined so as to replace the column into a successive thin wall with a cross-sectional area equivalent to the column. The input motions for the analyses both in the horizontal and vertical directions were given from 1-dimensional earthquake response analyses based on the multiple reflection theory, by the deconvolution to the base rock at the site from the recorded motion at the JMA Kobe station which is located on the outcrop near the site. Fig.4 shows the time histories of the input motion. The maximum accelerations of the input motions were 667 gals and 301 gals in the horizontal and the vertical directions, respectively.



γ_t (kgf/cm^2)	V_s (m/sec)	V_p (m/sec)	E (kgf/cm^2)	ν	h
1.7	140	700	1000	0.48	0.2
1.9	340	1600	6600	0.47	0.1
1.8	180	1640	1740	0.47	0.2
1.9	240	1640	3260	0.49	0.2
2.0	390	1640			0.1

Fig.3 Model for numerical simulations and dynamic properties of surface soil deposits

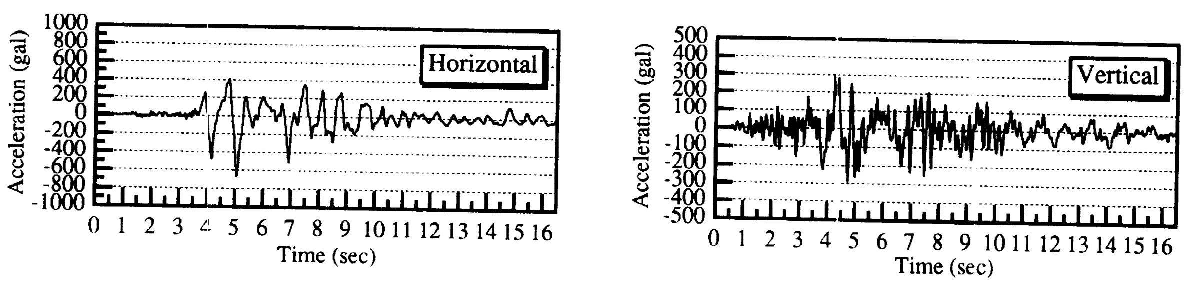
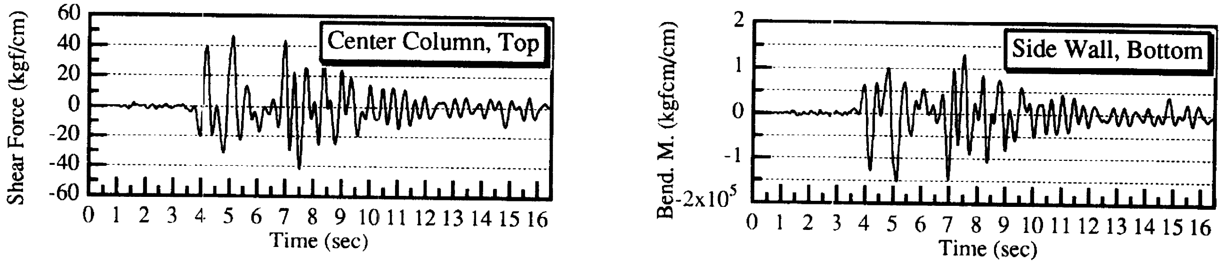


Fig.4 Input motions used in numerical simulations

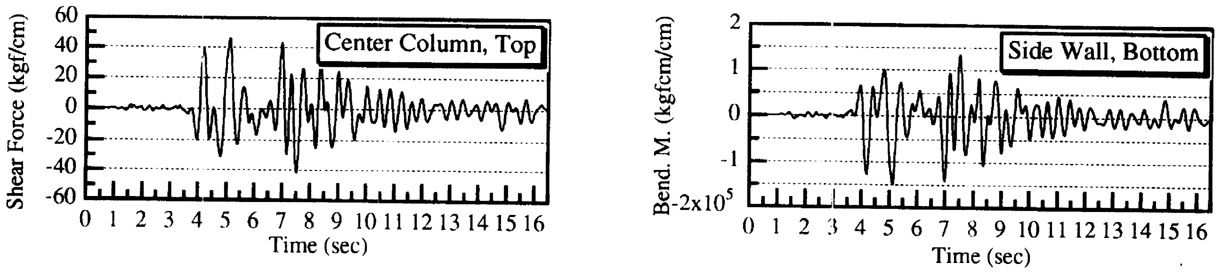
Three cases of earthquake response analyses were conducted according to the input condition: (1) Case-1 in which both horizontal and vertical motions are input; (2) Case-2 in which only horizontal motion is input; and (3) Case-3 in which only vertical motion is input. Comparison on the result of the three cases of analyses are shown in Fig.5 for shear force on a center column and for bending moment on a side wall, representing time histories of internal forces. The result of comparison can be summarized in the followings.

The axial force of the center column was originated mainly from the vertical vibration of the surface ground. The value of which, however, is much smaller than the value generated by the static earth pressure. Therefore, the collapse of center columns can not be explained only by the vertical ground vibration. Most of the shear force generated at the center column, on the contrary, is originated from the horizontal ground vibration as shown in Fig.5(a). The value of which reaches the level of the average allowable shear strength of concrete. The tunnel model used here is rough and does not necessarily represent the damaged subway. These results indicates, however, that the main cause of the damage would be the horizontal earthquake motion. Most of the bending moment and the shear force generated on side walls are originated from the horizontal earthquake motion, represented by Fig.5(b). Even a large part of axial force at the bottom of side walls is also governed by the horizontal motion. The values of moment and shear force both at the top and the bottom of side walls are much higher than their allowable levels.

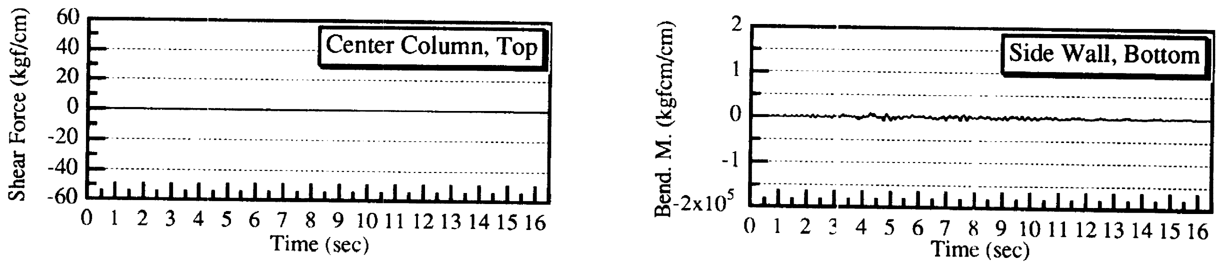
Because the stiffness of surface soil deposits is comparatively high, the relative displacement between the ceiling and floor slabs is almost identical with that of soil deposits at that depth. Though the maximum relative displacement between the ceiling and floor slabs analyzed was as small as 2 cm, it is considered to be large enough to deform a tunnel compulsorily to a extent so as to be disintegrated as shown in the photographs.



Case-1 (both horizontal and vertical input motions are applied)



Case-2 (only horizontal input motion is applied)



Case-3 (only vertical input motion is applied)

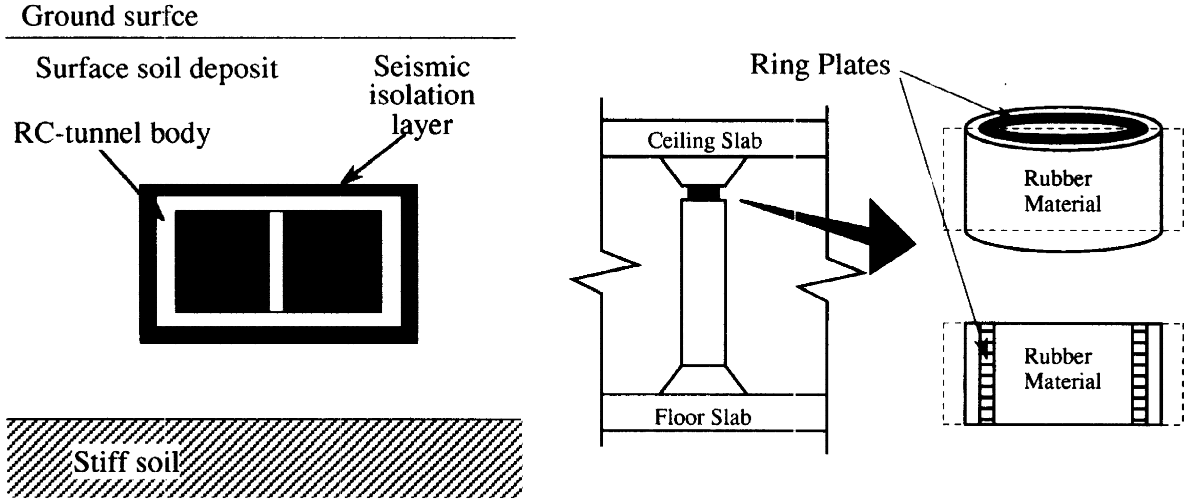
(a) Shear force of a column (b) Bending moment of a side wall

Fig.5 Time histories of shear force of a center column and bending moment at the bottom of right side wall

SEISMIC ISOLATION METHODS FOR UNDERGROUND STRUCTURES

Methods using seismic isolation layer covering a tunnel body

The seismic isolation method effective to highly improve seismic safety of underground structures have been presented by the author and the author *et al.* (Suzuki, 1990, Suzuki and Tamura, 1995). In the method, the soft isolation layer is formed between the tunnel and the surrounding soil as illustrated in Fig.6 The material properties necessary for the isolation layer are (1) low shear modulus, say, 5.0 kgf/cm2 and (2) high Poisson's ratio almost equals to 0.5. The latter property is indispensable to minimize the ground settlement over the tunnel. The material should be capable of large shear deformation and it should be highly water-resistent. Suzuki proposed this seismic isolation system and verified its effectiveness through model vibration tests using a shaking table (Suzuki, 1990). One of the material for an isolation layer proposed by the authors is rubber-like material mainly composed of liquified silicone-rubber (Suzuki *et al.*, 1995), which can be easily filled up the tale void in shield driving by injection from an inside of the tunnel, then the seismic isolation system can be established even for shield-driven tunnels as well as other urban tunnels constructed by the open-cut method. The isolation effect of the method was already discussed by the author for shield-driven tunnels with a round cross-section. Then, high seismic isolation effect in the tunnel axial deformation and comparatively low isolation effect in the cross-sectional deformation are shown (Suzuki and Tamura, 1995). In this paper, the seismic isolation effect of the method applied to the tunnel with a rectangular cross-section is examined by earthquake response analysis for a case that this method was applied to the Daikai station, focussing on a cross-sectional deformation during earthquakes.



(a) Isolation layer applied to a rectangular tunnel

(b) Isolation rubber placed at the top of a center column

Fig.6 Seismic isolation methods for underground structures applied to numerical simulations

<u>Method applying a device for shear deformation absorption to the top of a center column</u>

The method proposed in this paragraph is a simple one in which a device for shear deformation absorption is applied between a center column and a ceiling slab. Because this type of tunnel supports a high axial force by center columns in a static condition, the collapse of center columns due to an earthquake leads to the strategic damage as described in the previous chapter. If the center column is maintained in a sound condition, the complete collapse like the case in the Daikai station could not have occurred, even if the side walls were damaged. Therefore, this method is effective to a cross-sectional deformation during earthquakes. Fig.6(b) shows the schematic diagram of an example of the device. The device needs high shear deformation capacity and high capacity in axial force, but it does not need any damping. The rubber material is constrained its lateral deformation by steel rings covering the rubber. These rings are stratified and they can slide each other with a low friction. The cost of the device is much lower than that of the laminated high damping rubber usually adopted for seismic isolation of bridges and buildings. The device can be applied to a previously constructed tunnel as well as a new one.

EVALUATION OF THE EFFECTIVENESS OF SEISMIC ISOLATION METHOD

<u>Effectiveness of seismic isolation layer</u>

Earthquake response analysis was conducted for a case, in which the seismic isolation layer with shear modulus of 5 kgf/cm^2 is formed covering the subway station with 10 cm in thickness. Two-directional earthquake motions in Fig.3 are input in the analysis. The case of this analysis is named here as Case-4 to differentiate this analysis from the previous cases. The result of the analysis is compared with that of Case-1 in which no seismic isolation is made.

Fig.7 compares the time histories of tunnel internal forces generated at the bottom of the right side wall between the two cases. The maximum values in axial force, shear force and bending moment were reduced to almost a half by the application of the seismic isolation layer, which denotes that the seismic isolation effect using this method is considerably high in case of cross-sectional deformation of a rectangular tunnel. The extent of reduction in internal forces is remarkable especially at the main part of the time histories. Then, high isolation effect is attained even when the early stage of the main part of an earthquake motion.

Fig.8 illustrates the comparison of the distribution for internal force of a tunnel between two cases of analyses, at the time when the vertically accumulated shear strain of the surface ground reaches a maximum value. The scale is 10 times enlarged for a center column. The comparison denotes that the reduction in internal forces due to the isolation layer is large at corner parts of a tunnel where a large internal force is concentrated. However, the internal forces on center columns are little reduced by applying an isolation layer, because the relative displacement between the ceiling and floor slabs is not largely reduced.

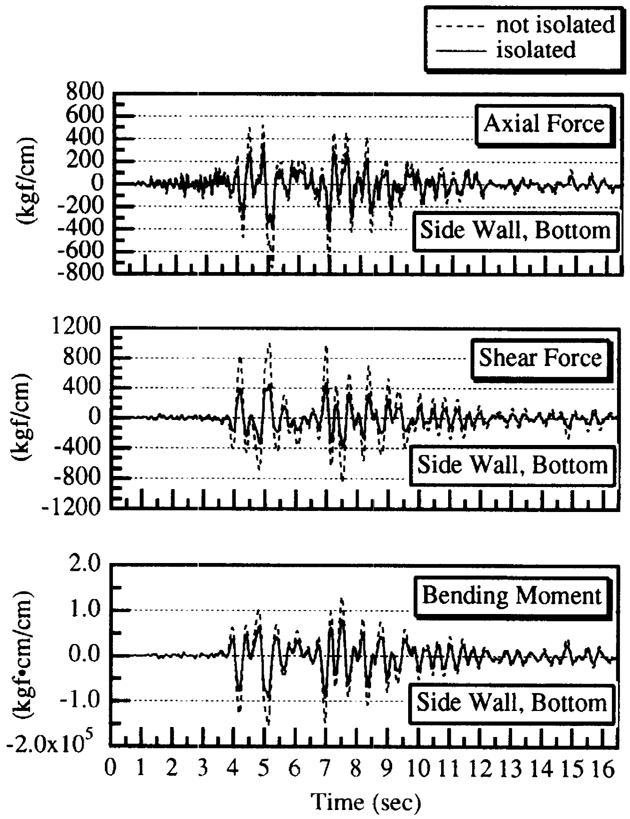


Fig.7 Comparison of time histories of internal forces

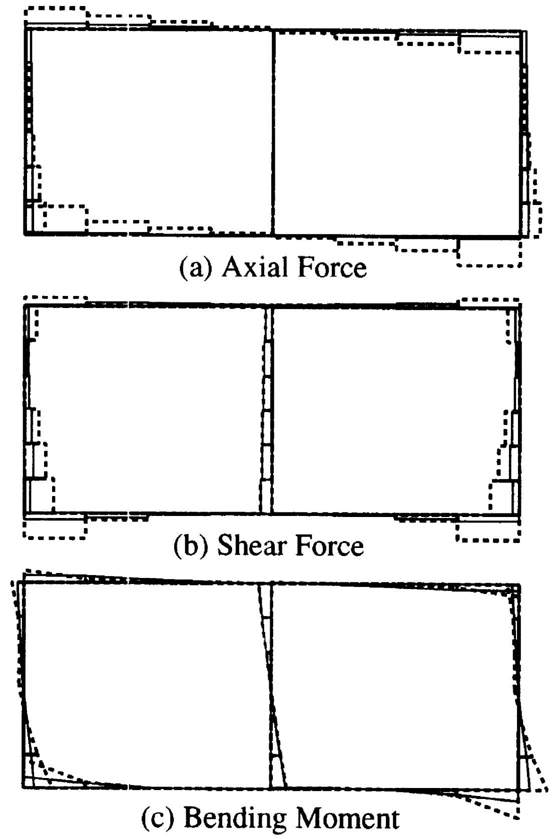
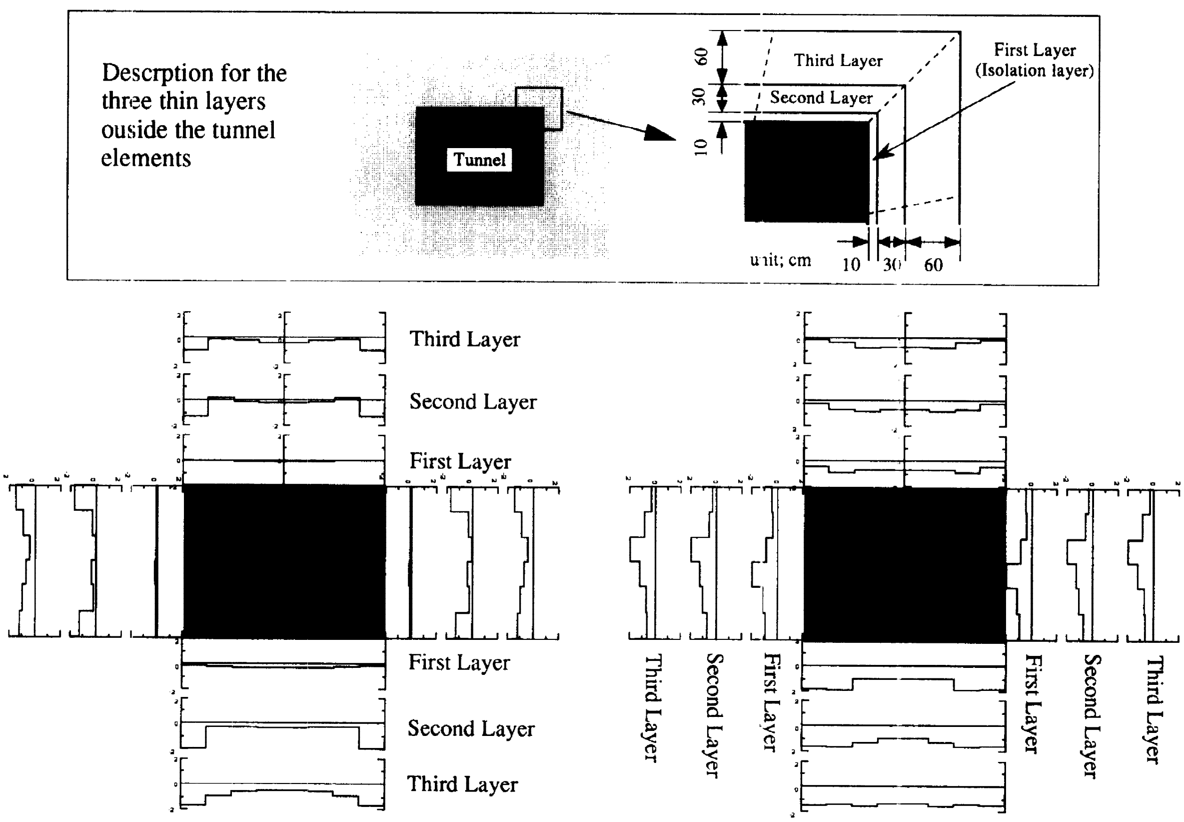


Fig.8 Comparison of internal force distribution



(a) Isolation layer is applied (Case-4) (b) No isolation layer is applied (Case-1)

Fig.9 Distribution of shear stress of thin layers around a tunnel

In order to clarify the mechanism of the seismic isolation, the shear stress of the isolation layer and surrounding two thin soil elements with a thickness of 30 and 60 cm, respectively, are illustrated in Fig.9. In the figure, the distribution of shear stress for three thin layers in Case-4 is compared with that in Case-1. All of the scales for shear stress in the figure are identical. When the isolation layer is not applied (Case-1), shear stress of the first layer around a tunnel is extremely large and the distribution forms for three layers are almost coincident with each other. When the isolation layer is applied, on the contrary, shear stress of the first layer (isolation layer) is extremely small. Shear stress of the second layer is also reduced to a certain extent and the distribution forms for the outer two layers are largely different from those in Case-1. The difference in shear stress distribution between two cases denotes that the effect of seismic isolation layer on the reduction of internal force of a tunnel is mainly explained by a drastic reduction of shear force acting around a tunnel which compulsorily deforms a tunnel.

Effectiveness of isolation rubber placed at the top of a center column

Earthquake response analysis was conducted for a case, in which the seismic isolation rubber of 30 cm in outer diameter and 20 cm in height is placed on the top of a center column. The shear modulus of rubber surrounded by steel ring plates is fixed to 5 kgf/cm^2 and that of Poisson's ratio is 0.5. Two-directional earthquake motions in Fig.3 are input in the analysis. This case of analysis is named as Case-5 here. As a result of the analysis, shear force at the bottom and at the top of a center column were reduced to 1/11 and 1/3, respectively and bending moment there were reduced to 1/330 and 1/2, respectively, in comparison with those in Case-1. When a center column is newly constructed, a large reduction of shear force and bending moment of a center column can be attained by placing such devices at both ends of a column.

CONCLUSIONS

This paper presents the typical damage of subway stations occurred due to the southern-Hyogo earthquake of January 17, 1995. Based on the damage investigation and numerical simulations for the damaged subway station, discussion on the main cause of the damage was made. Then, two seismic isolation methods for underground structures were introduced. Finally, the methods were applied to the damaged station in numerical simulations and the effectiveness of the two methods on the reduction of tunnel internal force was discussed. Conclusions derived in this paper are as follows:

(1) Main cause of the subway damage was estimated to be the horizontal earthquake ground motion.

(2) The method to apply a seismic isolation layer covering a tunnel is highly effective to the reduction of internal force due to cross-sectional deformation during earthquakes for a tunnel with a rectangular cross-section, though it can not contribute to the reduction of shear force and bending moment of a center column.

(3) The effect of seismic isolation layer on the reduction of internal force is mainly originated from a drastic cut of shear force acting around a tunnel.

(4) The method to place an isolation device with no damping on the top of a center column is effective to reduce column's shear force and bending moment. The collapse of a center column leads to a destructive damage, since it generally supports high earth pressure. Therefore, the application of this type of device with a low cost is practical.

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