Characteristics of reinforcement for earthquake resistance in mountain tunnel

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ABSTRACT: In Japan, some mountain tunnels are damaged by earthquakes and relative large-scale deformations such as the collapse of permanent lining and the deformation of supports have occurred. Although the earthquake resistant countermeasures for tunnels has been examined recently, some countermeasures for existing tunnels are performed on the result of tunnel inspection rather than the need against earthquake resistance. To clarify the effects and the mechanical behavior of countermeasures, the model experiment was conducted assuming the structure of actual road tunnels. The collapse mechanism was compared among the cases when various kinds of reinforcement to tunnel were performed, such as rockbolts, fiber sheet and rebar. Results showed that the improvement of load-bearing capacity of the tunnel was limited, however the prevention of falling concrete blocks from structure could be expected.

Keywords: mountain tunnel, earthquake, seismic measures, rehabilitation measures, experiment.

1 INTRODUCTION

Mountain tunnel is considered to be a relatively strong structure against earthquake because it behaves in accordance with the surrounding ground. However, even mountain tunnels have suffered collapse of linings and deformation of supports in limited numbers due to large earthquakes such as the Niigata Chuetsu (2004) and the Kumamoto (2016) in Japan. An earthquake resistant measure for typical road tunnels in mountain areas newly constructed in Japan is empirically single reinforcement bar installed in the permanent lining, because the behavior of mountains is uncertain and seismic damage is not easy to predict. However, some countermeasures for existing tunnels are performed based on the result of tunnel inspection rather than the need against earthquake resistance. A tunnel with reinforcement and rehabilitation measures can keep health condition to some degree, however, the examination of their effects on the mechanical behavior of tunnel is limited. Therefore, this study aims to assess the earthquake resistance effect of the deformation countermeasures currently being implemented in mountain tunnels. A two-dimensional static loading test was conducted to simulate deformation countermeasures for rock tunnel, and effects of some countermeasures on the tunnel permanent lining during earthquakes was examined.

2 EXPERIMENTAL METHOD

The mechanical behavior of tunnel structures under excessive forces caused by large earthquakes was investigated. The experiment was conducted by replacing seismic loads on a tunnel model installed in a soil tank simulating the ground with static loads from one direction.

Figure 1 shows the experiment apparatus. It consists of a soil tank enclosed by steel walls, assembled with three hydraulic jacks and reaction columns, that can apply static loads that suppose external forces by earthquakes.

The tunnel models were loaded from either the vertical or horizontal direction. The size of the soil tank is 1.2 meter in both length and width, and 0.3 meter in depth. Three sides of the walls of the soil tank are fixed, and one side is movable. There are three hydraulic jacks installed, and the loading capacity of one jack is 400 kN (total 1200 kN). The steel cover was placed on the soil tank to assume a plane strain condition during loading.

Table 1 shows the specification of the lining and the ground models. The size of the model was made to be 1/20 of a typical national road tunnel in Japan. The lining was made from plane mortar and the target uniaxial compressive strength was set to 18 MPa. The ground model was made from poor mixture mortar with targeted strength of 0.5 MPa.

The measurement items were the applied load, the inner displacements and the circumferential strain of the lining model. In addition, the cracking and failure conditions were visually observed.

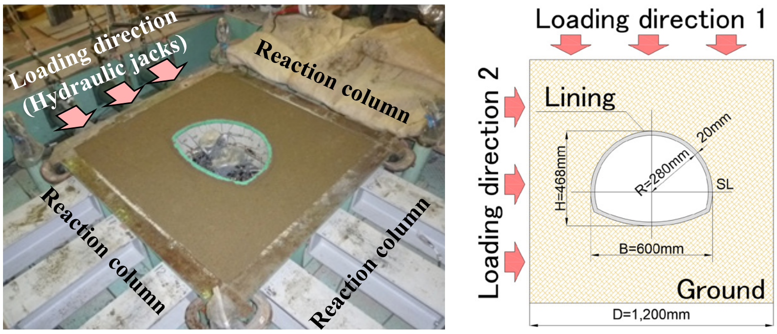

Figure 1. Outline of the model experiment.

Table 1. Specification of mortar lining and poor-mixture mortar for the experimental models.

Mortar for lining					Poor-mixture mortar for ground			
W/C	Unit Weight (kg/m^3)				W/C	Unit Weight (kg/m^3)		
(%)	Cement	Water	Soil	AE water reducer	(%)	Cement	Water	Soil
66.8	352	235	1575	3.52	191.8	55	105.5	1000

2.1 *Tunnel damage mode due to earthquakes and ground condition of the experiment*

The deformation shape of the ground during an earthquake is generally considered to be shear deformation. However, past earthquake damages with mountain tunnels has revealed that not only shear deformation but also compressive damage to the crown and side walls has occurred (Asakura et al.2000). Furthermore, a study by Kusaka et al (2016, 2019). that conducted dynamic measurements inside tunnels during earthquakes showed that tunnels were undergoing vertical or horizontal compression deformation. These results suggest that tunnels in areas with poor ground conditions, such as at the portal, may experience shear deformation during earthquakes, but tunnels in rock condition may experience not only shear deformation but also horizontal or vertical compressive deformation. Moreover, the ground where such deformation occurred was composed of soft to medium-hard rock.

Figure 2 shows the deformation and failure modes of tunnel during earthquake. In this study, the experiments assumed soft rock condition, that were conducted under vertical and horizontal loading conditions.

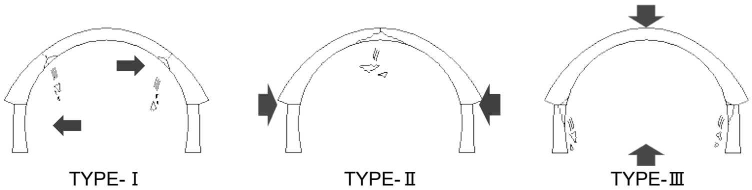

Figure 2. The deformation and failure modes.

2.2 Overview of Experimental Cases

Figure 3 shows the outline of the model experiment, and Table 2 shows the cases and conditions of the model experiment. The simulated cases in the experiment include no countermeasures and three types of countermeasures against earthquakes.

The Rebar is arranged in a single layer, that is a common reinforcement measure used in Japanese road tunnels with poor rock conditions. Additionally, this reinforcement measure empirically uses 19 mm diameter rebars without conducting structural calculations in the design phase. In the model experiment, the Rebar was used by arranging 1 mm diameter steel rods in a lattice pattern at 10 mm intervals, that was placed at the center of the lining model.

The Rockbolt is often used as a reinforcement measure for existing tunnels. The bolts were made of 3 mm diameter and 150 mm length brass stick, and sand attached to improve their anchoring with the ground model in this experiment. They were installed in two layers, with nine of them placed in the circumferential direction from the arch to the side walls at a pitch angle of 22.5 degrees.

The Sheet is often used as a repair measure for existing tunnels, that is made of carbon fiber, and the fiber density is 50 g/m^2. It was bonded from the arch to the sidewalls of the lining with adhesive.

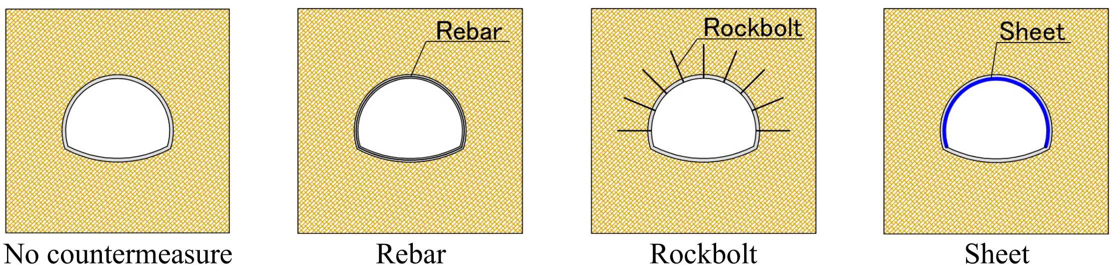

Figure 3. Outline of the model experiment.

Table 2. Cases and conditions of the model experiment.

No.	Load direction	Countermeasure	Material	Material properties of specimen: Ground UCS (MPa)	Lining UCS (Mpa)	Lining Young's Modulus (Gpa)	Lining Poisson's ratio
#1	Vertical	---	---	0.431	24.7	15.0	0.19
#2		Rebar	Wire mesh*	0.444	18.8	12.5	0.19
#3		Rockbolt	Brass stick**	0.566	21.1	14.4	0.19
#4		Sheet	Carbon fiber***	0.465	32.3	17.3	0.20
#5	Horizontal	---	---	0.486	23.8	14.3	0.17
#6		Rebar	Wire mesh*	0.478	18.1	13.0	0.19
#7		Rockbolt	Brass stick**	0.458	21.8	14.9	0.19
#8		Sheet	Carbon fiber***	0.478	24.2	15.8	0.19

* Place wire mesh with a diameter of 1 mm and spacing of 10 mm in a lattice pattern around the entire circumference of the lining.

** Install brass sick with a diameter of 3 mm and a length of 150 mm in two rows at a 22.5 degree angle interval on the arch and sidewall.

*** Place a 50 g/m^2 fiber sheet on the arch and side wall.

3 RESULTS AND DISCUSSION

The load-displacement curves are shown in Figure 4 and Figure 5. The displacements show positive value when the tunnel cross sections shrink and negative value when they expand. As a result of all cases, the displacements of the tunnel cross-section in the same direction as the load increased. On the other hand, the displacements of the tunnel cross-section perpendicular to the load direction decreased when the load is small and then increased after the curve changes.

In the cases of Rebar, the loads at the curved change point were smaller than no countermeasure cases. However, the fact that the uniaxial compressive strength of the lining in rebar cases are smaller than that of the other cases is a contributing factor, therefore, the interpretation of the results is sensitive. Additionally, the final displacements in the loading direction are larger than in the case no countermeasure cases, suggesting that even if deformation and cracking occurred due to external forces, the rebars prevented collapse by fixing concrete blocks. On the other hand, the final displacements in the direction perpendicular to the loading direction were smaller than that in the case no countermeasure, that is considered to be due to the increased stiffness of the lining model by the rebars, which suppressed deformation. These results indicate that the reinforcement by rebar inside the lining is effective.

In the cases of Rockbolt, the loads at the curved change point were lager than the no countermeasure cases. Therefore, the placement of rockbolts on permanent lining has the potential to increase the load-bearing capacity of the tunnel structure. The final displacements in this case were also larger than those in the case with no countermeasures. As in the rebar cases, this may indicate that deformation occurred, but collapse of lining model did not occur due to the sewing and hanging effect of the rock bolts.

In the cases of Sheet, the loads up to the point of curve change are larger than that in the no countermeasure cases, as in the rock bolt case. Therefore, there is a possibility that the installation of inner reinforcement by fiber sheet over the permanent lining can be expected to improve the load carrying capacity at the serviceability limit level. However, it should be noted that the sheets in this experiment were applied to the whole surface over the permanent lining, which is a wider area than in actual practice. The sudden increase in the displacement occurred at the curve change point in the vertical loading case, suggesting that some kind of failure occurred at this time, which may also be due to the high uniaxial compressive strength of the lining.

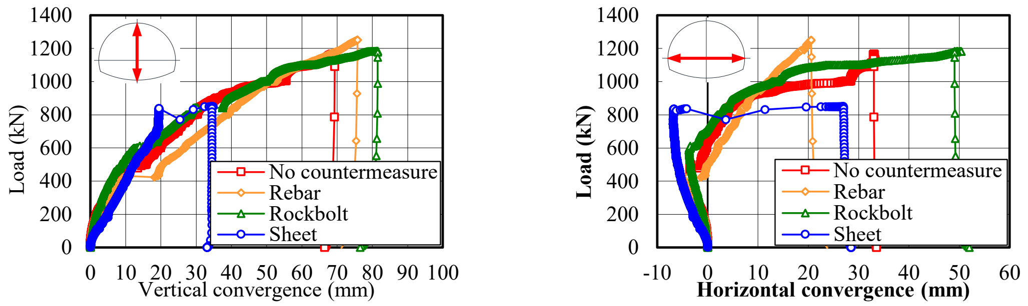

Figure 4. Load-displacement curves (Loading from vertical direction).

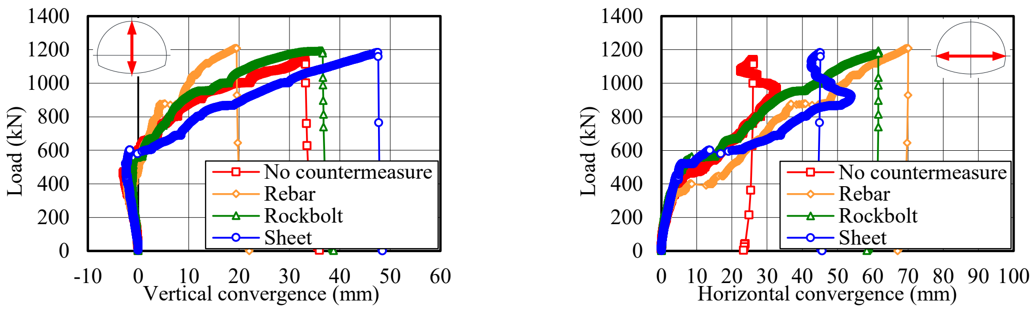

Figure 5. Load-displacement curves (Loading from horizontal direction).

Figure 6 and Figure 7 show recorded development of the cracks and failures on the inner surface of the lining models during loading.

The cases of Rebar showed less cracks and compression failures around the crown than the no countermeasures cases. Therefore, installation of rebar may be expected to reduce the fall of the concrete around crown.

The cases of Rockbolt have some cracks in the circumferential direction of the whole lining due to stress transmission from the rockbolts. If the cracks become blocked, the separated pieces of the lining may fall. On the other hand, in the horizontal direction loading case, the failure of the crown is suppressed, and depending on the sewing and hanging effects of the rockbolts, it may be possible to suppress the falling of pieces of the lining. Therefore, when using rockbolts as a countermeasure, it is desirable to combine them with other countermeasures such as sheet that attachment can control the collapse of pieces of permanent lining.

The cases of Sheet also showed less cracking and compression failure around the crown. Therefore, it can be expected that the sheet will also limit the falling of pieces of lining around crown. In the vertical loading case, the failure occurred at the invert section. Although bending occurred at the crown and the invert, the invert section was not reinforced and had a small radius of curvature, which may have caused a sudden failure at the section. On the other hand, in the horizontal loading case, the failure due to bending does not occur because the axial force acts on the crown and the invert, and the sidewalls affected by bending do not fail because of reinforcement by the sheet, resulting in a different failure mode from the vertical loading case. Therefore, when using sheeting as a countermeasure, it is necessary to consider the effect on the areas where sheeting is not installed, such as inverts and corner joints.

The treatment of the connection between the sidewall and the invert is desirable, because the main failure occurs at that point in all experimental cases, which may be the weak point of the tunnel structure.

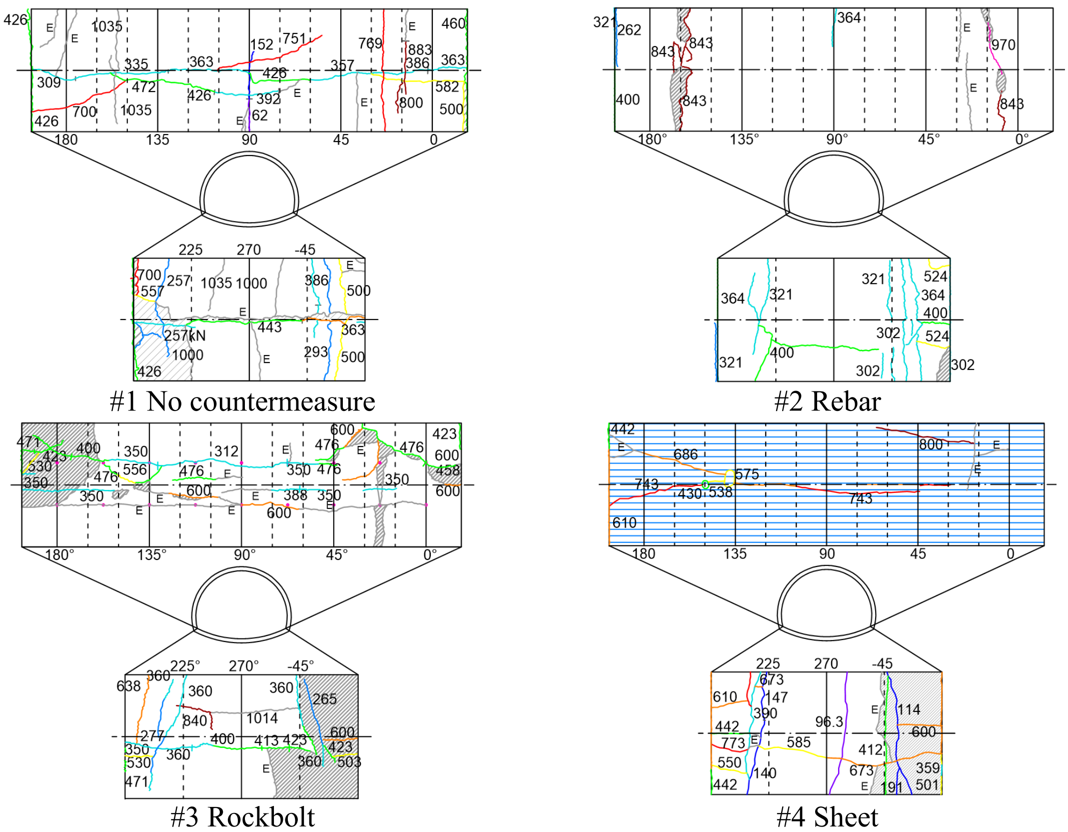

Figure 6. Cracking and failure status of the lining model (Vertical load direction).

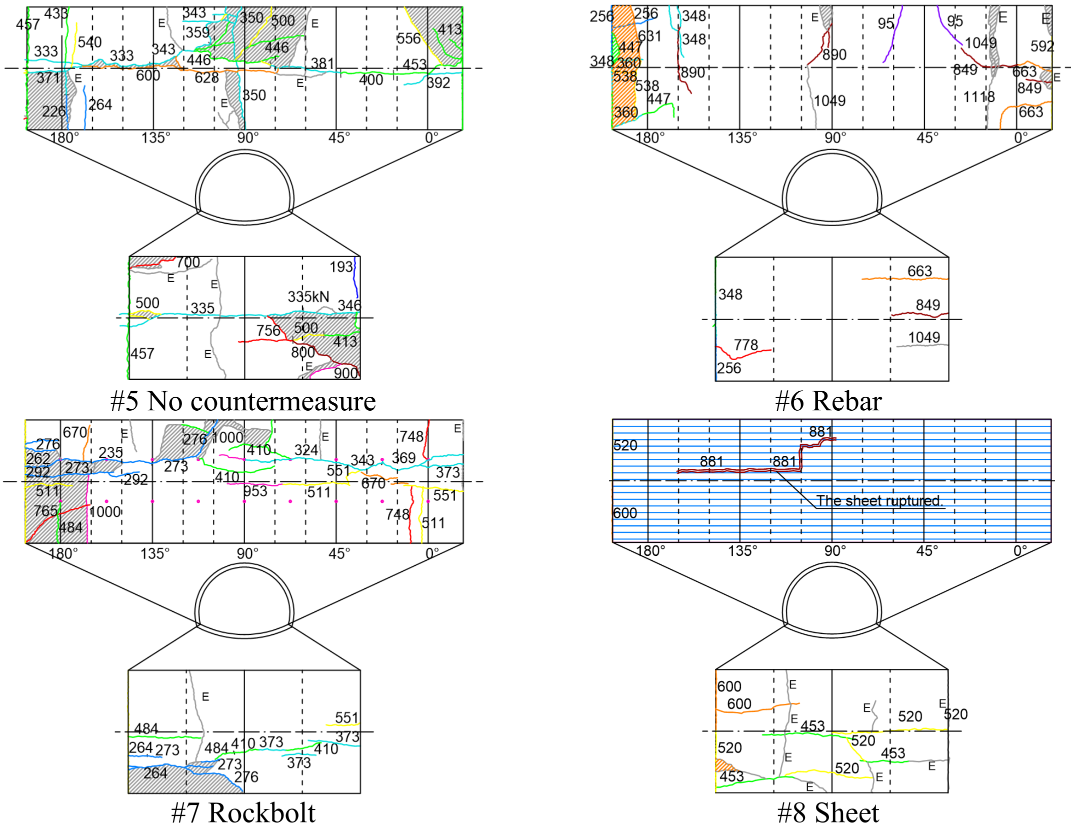

Figure 7. Cracking and failure status of the lining model (Horizontal load direction).

4 CONCLUSIONS

Static loading test was carried out assuming that soft rock tunnels, that was affected by vertical and horizontal compressive deformations caused by earthquakes to identify the effects of the countermeasures in existing tunnels.

It is suggested that the installation of deformation countermeasures on existing tunnels may improve the load-bearing capacity of tunnel in terms of usability (until initial cracking), depending on types of the countermeasure. Furthermore, the deformation countermeasures may delay the fall of blocks of lining because that may reduce the occurrence of cracks and failures at tunnel crown.

As a seismic countermeasure for existing tunnels, it is necessary to ensure the load-bearing capacity of lining through proper maintenance, and to take measures to prevent sudden collapses that may cause harm to users even if deformation occurs.

This experiment assumed a soft rock ground conditions, however, it is necessary to conduct analytical studies and discussions on poorer ground and harder rock conditions in the future.

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