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SEISMIC PERFORMANCE OF FLAT CROSS-SECTIONAL TUNNEL WITH COUNTERMEASURES

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SUMMARY

This paper presents a new concept of the seismic countermeasure for a structurally special part of tunnel such as ramp of road tunnel and a crossover of double-truck railway tunnel, in which a flat and large cross-sectional tunnel and a junction of tunnels appear. Since seismically high stability is required for it, a series of centrifuge model tests of cross-sectional tunnel and ground system with following countermeasures were conducted in the transverse direction: (1) isolation layer around outer surface of tunnel; (2) ground improvement by cement-solidification surrounding tunnel; and (3) combination of the former ones. As a result, combination method can be assumed to be most effective, and the effectiveness of the seismic deformation method in the seismic design of such tunnels is experimentally verified.
Additionally, a cost-effective material for the seismic isolation layer is proposed with considering its cyclic properties, which can be applied to a flat cross-sectional tunnel and a junction of tunnels.

INTRODUCTION

Since the collapse of subway Daikai Station in The 1995 Kobe Earthquake that was a grave warning for the necessity of the seismic design of tunnels, it has been regarded as an important problem in the design of tunnels in Japan.
In the meanwhile, according to the development of driving machines of shield tunnels which is applicable to rapid work, continuous long-distant work, complex and large cross-sectional work, and curve-driving work, shield tunnels have been applied more and more to construct water supply, sewerage, electricity line, railway and road around urban area in Japan. In addition, construction projects to develop circular routed expressways around urban areas according to a Japanese government policy of urban redevelopment are widely noticed, which projects are planed to be developed by tunneling method and necessitate difficult construction techniques of tunnels such as flat cross-sectional tunnel and underground junction without open-cut of the ground. Such structurally special tunnels are in severe seismic condition in the tunnel's design compared with straight and circular cross-sectional tunnels. So it is important to develop the seismic design techniques and the stabilization method applicable to Level-2 ground motion

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(which is induced by strong earthquake and is of rare occurrence during lifetime of structures) as well as construction techniques for such special tunnels.
Then, the authors took up seismic problem for a ramp of road tunnel and investigated its seismic performance. First, dynamic 3D FE analysis was performed in order to grasp its performance and clarify the problems. Next centrifuge model tests were carried out for flat cross-sectional tunnels accompanied with the seismic countermeasures. Finally, a new concept of the countermeasures is proposed utilizing existing construction procedure and a cost-effective material for the seismic isolation layer.

SEISMIC PERFORMANCE OF RAMP STRUCTURE OF ROAD TUNNEL

Overview and schematic representation of a ramp structure of road tunnel are shown in Figure 1 and 2.
The ramp structure can be confirmed to consist of followings: (1) a part of tunnel to diverge or converge, which cross-section is flat-shaped; (2) a part around the nose of the tunnel; and (3) a ramp tunnel. Three-dimension finite element analysis assuming tunnel-ground system shown in Figure 3 was conducted in order to verify its seismic performance (Ohbo, N. et al, 2004). In which, two lanes at main road and single lane at ramp road are assumed and the system was modeled in detail by solid elements. The results subjected to Level-2 ground motion (Earthquake Record by Kobe Marine Observatory in The 1995 Kobe Earthquake) are shown in Figure 4. From these figures, it is observed that stress concentrations take place around the nose and the ramp tunnel according to the difference of earthquake response between tunnel and ground. In addition, sectional force of flat cross-sectional tunnel changes remarkably in the transverse direction. Hence, it follows that evaluation of earthquake resistance of flat cross-sectional tunnel in the transverse direction and the reduction of sectional forces from the nose to the ramp tunnel are required in the seismic design.

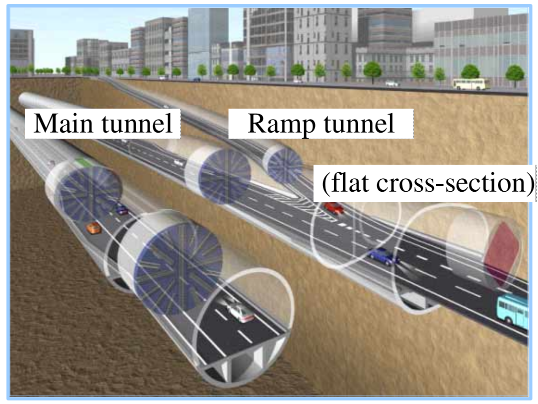


Figure 1: Overview of an example of ramp structure in road tunnel

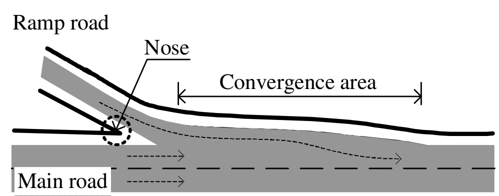


Figure 2: Schematic presentation of ramp structure (in case of convergence side-ramp way)

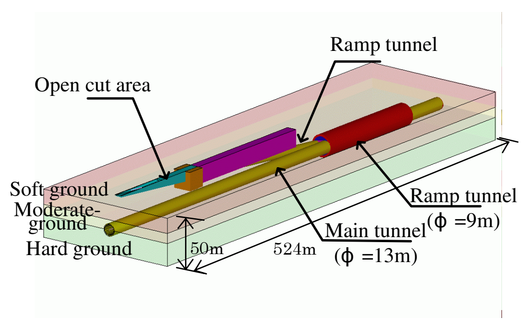
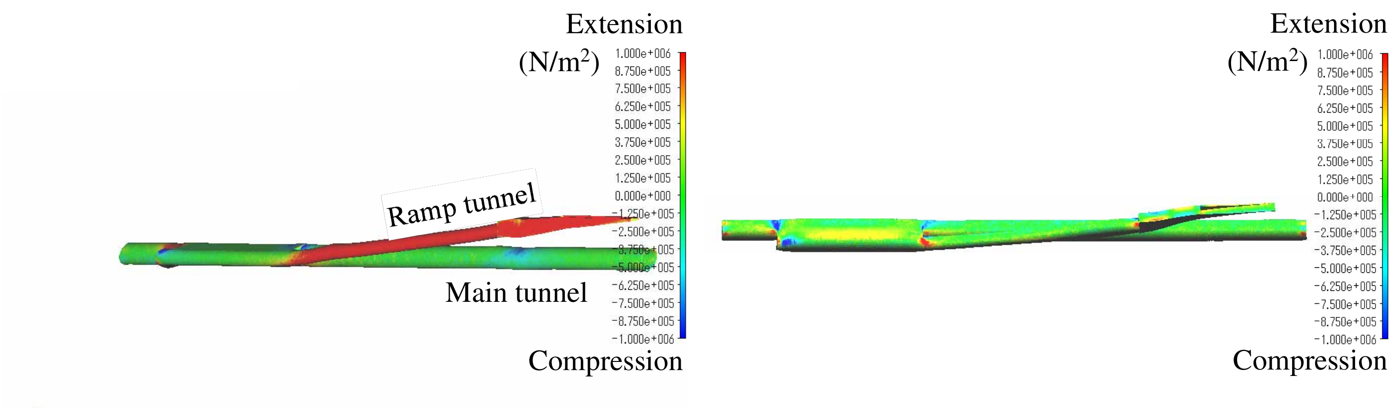


Figure 3: Model of 3D finite element analysis (Ohbo et al, 2004)

SEISMIC PERFORMANCE OF FLAT CROSS SECTION TUNNELS WITH COUNTERMEASURES

Centrifuge Model Tests

Centrifuge model tests summarized in Table 1 were carried out in order to study earthquake resistance of flat cross-sectional tunnel in the transverse direction.
In all the tests, the ground models was prepared by pluviating dry Toyoura sand (specific gravity: 2.64, maximum void ratio: 0.978, minimum void ratio: 0.605) to achieve a relative density of 80-90% in a shear box;



(a) excitation in longitudinal direction **(b) excitation in transverse direction**

Figure 4: Stress distribution in longitudinal direction of tunnel (Ohbo et al, 2004)

the tunnel model was installed in position during the placement of the sand; and dynamic or static loading was applied to the shear box after the model was put in the centrifugal acceleration field. The tunnel model was flat cross-sectional, which outer width and height is 100mm and 65mm, and the material was aluminum or mortar (compression strength 21N/mm^2) to get linear-elastic-behavior or failure-process of the tunnel respectively. At the both ends of the tunnel models, measures were taken to reduce friction between the tunnels and the shear box. In some cases of the tests, seismic countermeasures for the tunnel were taken as follows: (1) Rubber membrane (thickness: 1.0 mm, elastic modulus: about 1.5 MN/m^2) was glued around outer surface of tunnel as a seismic isolation layer (hereafter, this case is called as "RM"); (2) Round-shaped solidified ground (unconfined compression strength: 1.0 MN/m^2) was arranged surrounding tunnel as ground improvement (hereafter this case is called as "SC"); and (3) combination of those ones (hereafter this case is called as "RM+SC"). Where, round-shaped solidified ground with its unconfined compression strength 2.0 MN/m^2 was used only for the test case of mortar model in combination cases.

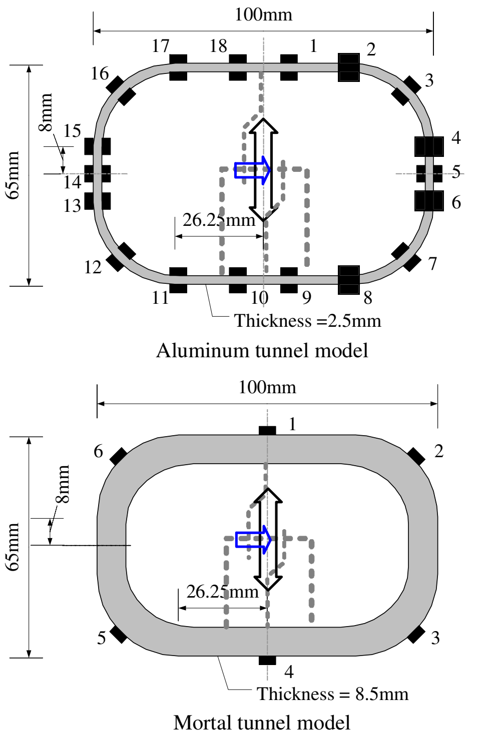
Table 1: Cases of centrifuge model tests for flat cross-sectional tunnels

Test Name	Ground Height	Tunnel Model			Centrifugal Acceleration	Loading	
		Material	Type	Counter-measures		System	Loading Pattern
CASE1d-2003	300mm	Aluminum (size: 100mm*65mm)	1	None (NC)	50G	Shaking Table & Shear Box by KATRI (Box Size: W500*L200*H330mm)	Dynamic Loadings (Step by step Sine-Waves are subjected)
CASE2d-2003			2	Rubber Membrane (RM)			
CASE3d-2003			3	Solidified ground by cement (SC)			
CASE4d-2003			4	RM+SC			
CASE1s-2003			1	NC		Active Type Shear Box by TIT (Box Size: W450*L200*H325mm)	Monotonic Loading
CASE2s-2003			2	RM			
CASE3s-2003			3	SC			
CASE4s-2003			4	RM+SC			
CASE1-2002	280mm	Mortal (size: 100mm*65mm)	5	NC	40G	TIT, Shaking Table & Shear Box by TIT (Box Size: W440*L150*H290mm)	Dynamic Loadings (Step by step Sine-Waves are subjected)
CASE2-2002			6	RM+SC			

Notes: KaTRI : Kajima Technical Research Institute TIT : Tokyo Institute of Technology
Overburden depth of tunnel is 117.5mm in all cases.

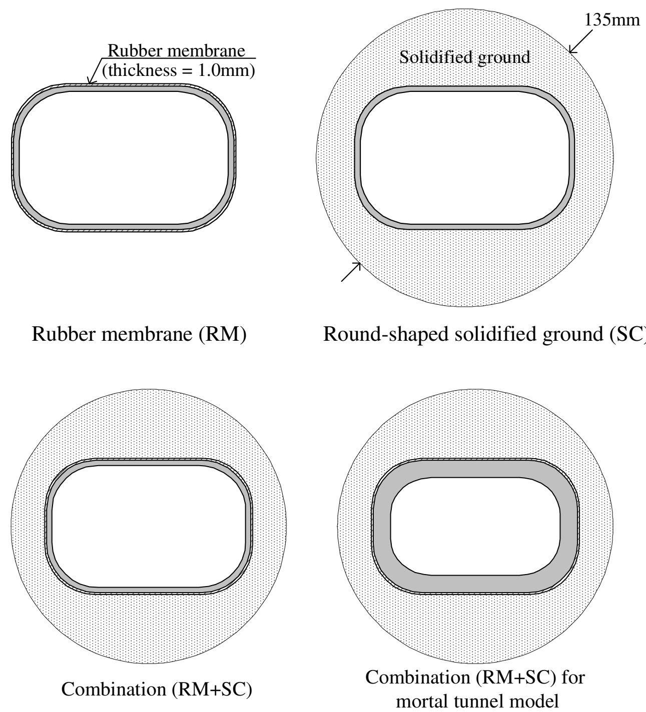
In dynamic loading cases, the unidirectional sinusoidal wave was inputted step by step from the shaking table, in which, the wave number was 20 cycles, the frequency was 100Hz, and the maximum acceleration was increased from 5G to 20G by 5G increments. In static loading cases, the active type shear box shown in Figure 7 was employed (Takahashi, A. et al, 2001, Yamada, T. et al, 2002) and the triangularly-shaped horizontal displacements were applied to the laminae.

Measurement sensors were installed in the central section of the tunnel model. Strain gauges were put on cross-section of the model in order to measure the bending strain component and the axial strain component respectively. Moreover, three none contact displacement sensors were set inside the model to measure the vertical and horizontal relative displacements between the top and bottom slabs of the tunnel. In addition, the ground accelerations, the settlement of the ground surface and the displacements of the laminae were measured by accelerometers, laser displacements meters, and potentiometers respectively.



■ :strain gauge ; The number of superscripts or subscripts attached strain gauges indicates the number of the strain gauge ; ⇨ : displacement sensor ; In cases of static loading tests, strain gauges (2,4,6,8,10,11,13,15,17,18) are ignored in measurement.

Figure 5: Outline of tunnel models and measurements



former 3 types are applied to aluminum models

Figure 6: Investigated seismic countermeasures

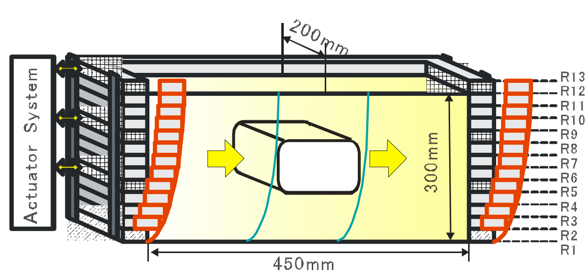


Figure 7: View of the Active type shear box

Tests Results and Discussion

Aluminum Tunnel Model behavior – Dynamic Loading Series -

Vertical displacements of the top slab relative to the bottom slab during the process of increasing acceleration up to 50G are shown in Figure 8. From the figure, it can be observed that the height of the tunnel becomes lower with increasing acceleration in all the cases and the quantity of the height reduction differs in each case. It is concluded that the seismic isolation layer does not reduce the vertical relative displacement much. On the contrary, the ground improvement obviously reduces the displacement. When RM+SC is compared with SC, it is shown that the displacement of RM+SC is larger than that of SC.

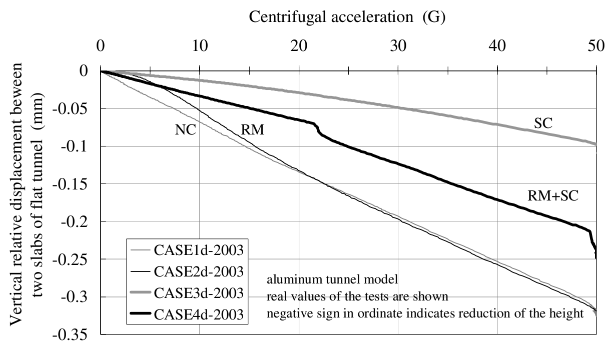


Figure 8: Vertical displacement of tunnel at increasing centrifugal acceleration

Figure 9 shows the bending moment and the axial force of the tunnel at the centrifugal acceleration of 50G. In case of NC, the bending moment becomes greater at the sidewalls and the centers of slabs, and axial force is great at the sidewalls. Sectional forces in the case of RM are almost the same as those in NC. So the influence of rubber membrane is quite small on the behavior of the tunnel at static condition. The bending moment in SC is the smallest in all cases. But the axial force is found to be most great. In RM+SC, the bending moment shows the same decreasing trend as the SC case. Moreover, the axial force decreases at the sidewalls either contrary to the SC trend and show the smallest value in all cases.

The above-mentioned results, which represent the performance of flat cross-sectional tunnel at the centrifugal acceleration, are summarized as follows:

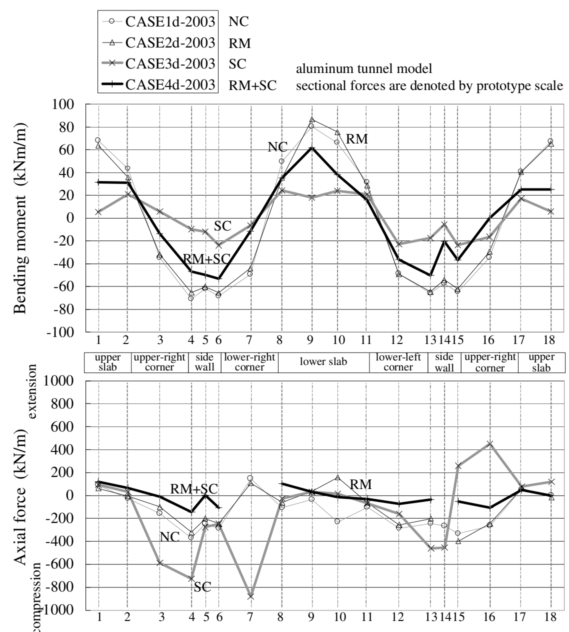


Figure 9: Distribution of sectional forces at centrifugal acceleration 50G

(1) In case of NC, the bending moment becomes greater at the sidewalls and the centers of slabs, and the axial force shows great at the sidewalls.

(2) Behavior of tunnel in case of RM is almost similar to that of NC either for the deformation and the sectional forces.

(3) In case of SC, the tunnel deformation decreases dramatically, but the axial force at sidewalls becomes great compared with NC while the bending moment remarkably decreases. It can be deduced that the tunnel performs with the surrounding solidified ground in a body.

(4) Combination of RM + SC affects not only the decrease of the tunnel deformation but also the decrease of the sectional forces. The reason why the sectional forces decreases in contrast to the axial

force concentration at the sidewalls in case of SC can be assumed that the rubber membrane isolates the loads from the solidified ground to the tunnel body as an isolation layer.

Next, the results of tests in dynamic loadings are shown and are discussed.
The amplitude per one wave of the vertical and horizontal relative displacement between the two slabs of the tunnel is shown in Figure 10. From this figure, the vertical and horizontal displacement have a almost linear relation with the acceleration in all cases. Compared with NC, the horizontal displacement of SC is smaller, however the vertical displacement is larger, which trend is shown in RM+SC. Thus, by constructing the ground improvement, the rate of the horizontal displacement and vertical displacement changes.
Here, the distributions of the sectional forces are shown in Figure 11.
In case of NC and RM, the bending moments and the axial forces at the corners show the peaks, Thus, the distribution of the sectional forces is of the same trend. Moreover, the sectional forces and acceleration increase with the input acceleration.
There seems to be a tendency that the bending moment in case of RM is smaller than that in case of NC. But the difference is quite small. As former studies, the seismic isolation layer is effective in reduction of the dynamic sectional forces due to isolate the transmission of seismic ground strain to a tunnel body (Suzuki, T. et al, 2000). But the effectiveness depends on the ratio Giso/Gg (Gm: shear modulus of isolation layer, Gg: shear modulus of ground) and is obviously greater as the ratio is smaller than 0.01(Zhi, H. et al, 1999). In this study, Giso/Gg varies nearly 0.01 to 0.05 as the ground becomes plastic due to the increase of the input wave acceleration, which ratios are great compared with the value 0.01. It seems to be a reason why the effectiveness of RM isn't obvious in this study.
In case of RM+SC, the bending moment and the axial force at the corners show the peaks, which trend are similar to the cases of NC and RM. Contrary, in SC, axial force is remarkably great at the sidewalls although the moment almost coincides with other cases. Therefore, the distribution of the sectional force in SC is a different trend. If a tunnel is of circular, shear stress takes maximum value at the side parts, and surrounding shear stress becomes great at the side parts. So the sectional force in SC seems to be concentrated at the side parts by the same reason. In RM+SC, the seismic isolation layer reduces surrounding shear stress of the tunnel; therefore the axial force can be decreased at the side part rather than the case of SC.
The results about the performance of the flat cross sectional tunnel under the ground excitation are listed below:

(1) The sectional forces of flat tunnel become great at the corners.
(2) In case of RM, the tendency which sectional forces is less than the case of NC appears, but the difference between the two cases is little in this study due to the reason that the ratio Giso/Gg in this study is greater than the value 0.01, which is regarded as an criterion for the effectiveness of isolation layer respected.
(3) In case of SC, the horizontal relative displacement between the two slabs decreases compared to the other cases. On the other hand, the vertical relative displacement becomes great. The bending moment is almost the same as the case of NC. Furthermore the axial forces of the side walls becomes greater than the case of NC.
(4) In case of RM+SC, the vertical relative displacement becomes the greatest among the cases. On the other hand, the horizontal relative displacement and the sectional forces almost coincide with the results of the case RM.

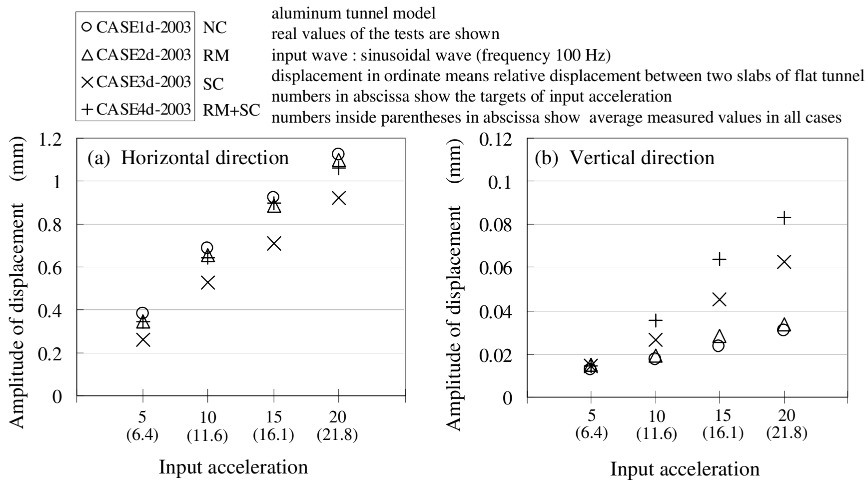


Figure 10: Amplitude of relative displacement between two slabs of flat tunnel during dynamic loading

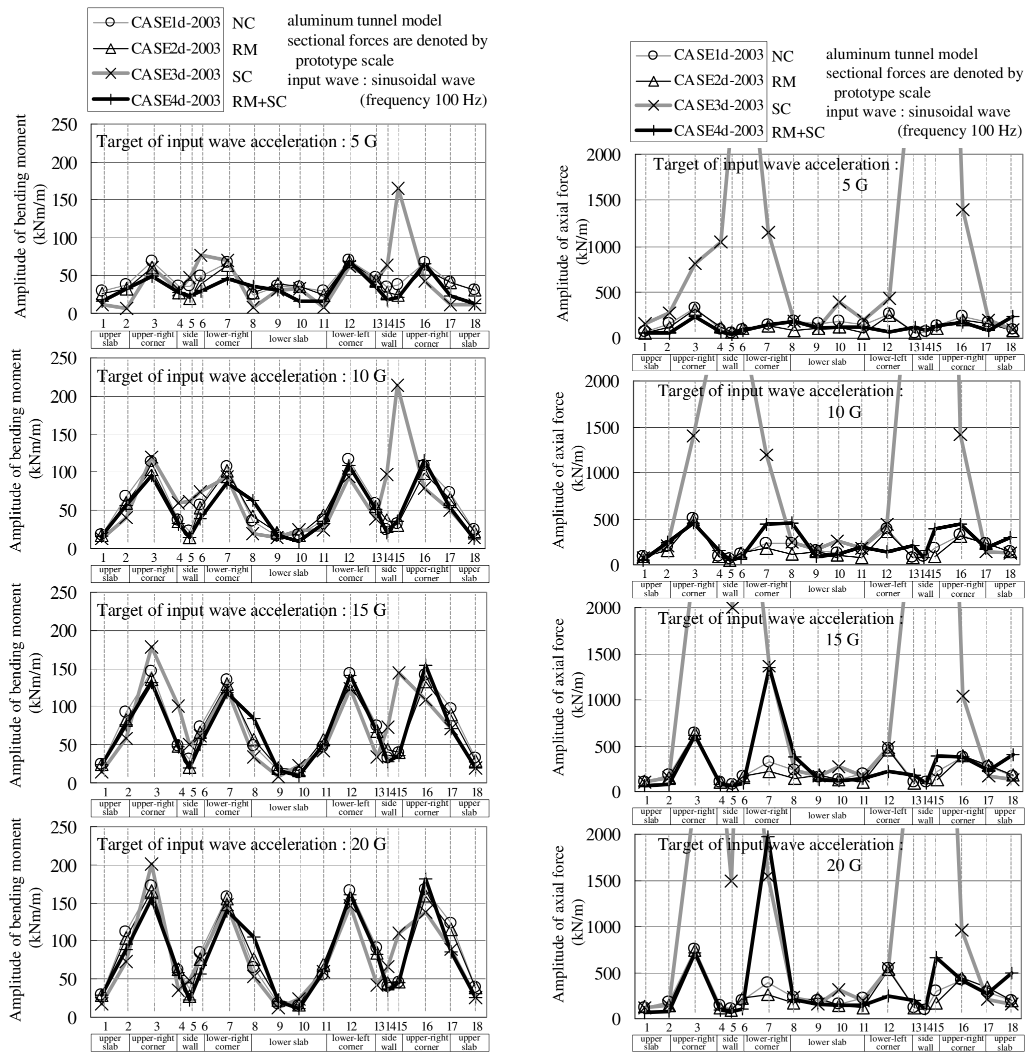


Figure 11: Amplitude of sectional force of flat tunnel during dynamic loading

The above-mentioned results reveal that the RM or the RM+SC has an advantage as a countermeasure of the tunnel under seismic excitation because the sectional force becomes smaller.
Considering the performances of the flat cross-sectional tunnels with the seismic countermeasures mentioned above in the two stages: one is in the centrifugal acceleration stabilized and the another is in the dynamic loading subjected, the combination measure of the isolation layer and the ground improvement can be respected to be most effective in all the cases. The reason is that the improved ground contributes to the reduction of the sectional forces and the vertical deformation at the static condition, and the isolation layer is assumed to reduce the sectional forces at the seismic condition. Furthermore, it can be deduced that the improved ground contributes to avoid the abrupt fracturing, deathblow, of the tunnel due to the reduction of the earth pressure acting on the tunnel like a kind of arching effect, according to the occurrence of the deformation during Level-2 ground motion.

Aluminum Tunnel Model behavior – Static Loading Series -

Static test results are compared with those of dynamic tests, when horizontal relative displacement is the identical value. Sectional forces of the case of RM+SC are shown in Figures 12.
The bending moment and the axial force are of the same trend and are almost identical in the figures. Thus, it can be considered that deformation of underground structure is controlled by the strain or relative displacement of the ground. The same trend is shown in all cases. So the seismic deformation method is judged to be reasonable for tunnel's seismic design with and without the countermeasures.

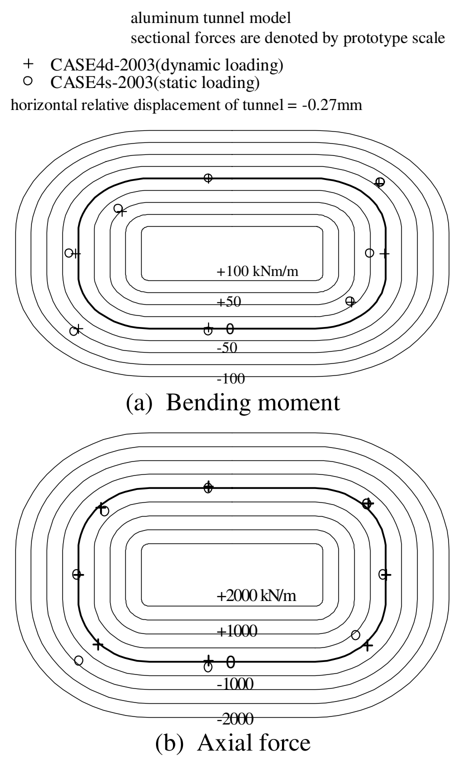
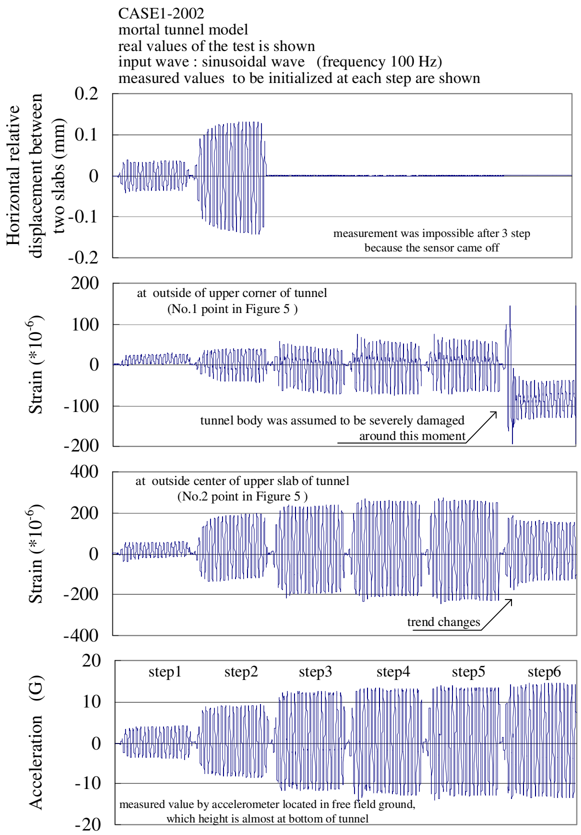


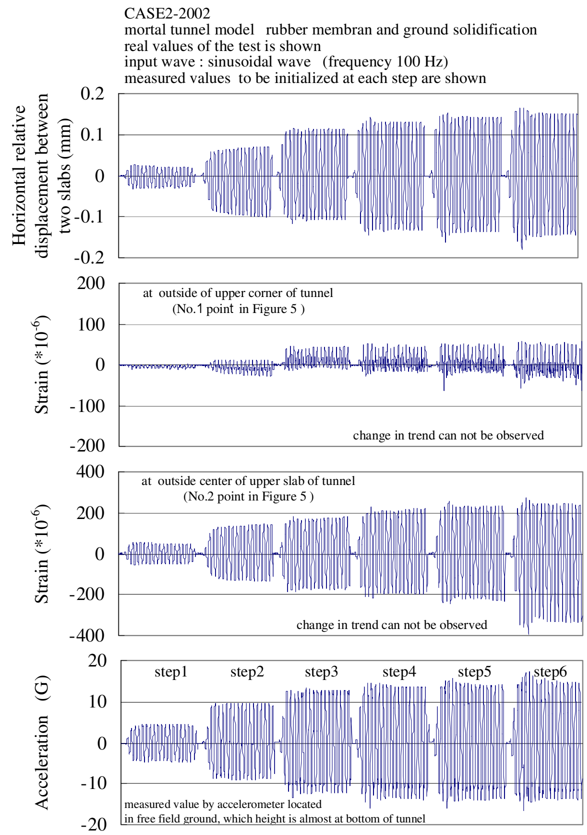
Figure 12: Comparison of sectional forces between dynamic loading test and static loading test for combination-measure cases

Mortal Tunnel Model behavior – Dynamic Loading –

In order to observe the fracturing process of the tunnel and verify the effectiveness of the combination type seismic countermeasure subjected to large ground excitation, the centrifuge model tests are carried out using the mortar tunnel models. The results are shown in Figure 13, in which the ground acceleration, the strains of the tunnel, relative displacements of the tunnel and the time history relations are shown. Moreover overviews of the tunnels after those tests are shown in Photo 1 and Photo 2.
From these figures, the body of the mortar tunnel model was cracked at the corners and the centers of the slabs where are the same loci that the sectional forces increase in the aluminum model. Furthermore the subsidence took place according to the occurrence of the cracks. In the meantime, the mortal tunnel model with the countermeasure wasn't damaged entirely. Thus the combination of isolation layer and ground improvement was verified to be effective as an seismic countermeasure of the tunnel in the condition that the tunnel without the countermeasure becomes remarkably damaged in severe ground motion.



(a) without countermeasure(CASE1d-2002)



(b) with countermeasure(CASE2d-2002)

Figure 13: Test results for mortal tunnel model

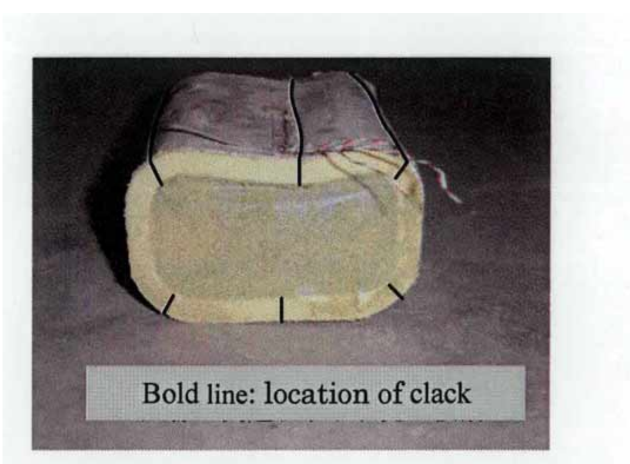


Photo 1: View of tunnel without countermeasure after the test (CASE1d-2002)

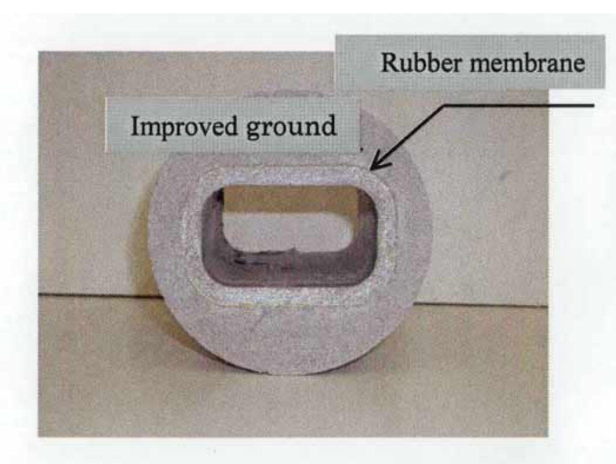


Photo 2: View of tunnel with countermeasure after the test (CASE2d-2002)

Work procedure of the tunnel with Isolation layer & Ground Improvement

For example, the flat cross-sectional tunnel with isolation layer and ground improvement can be constructed as illustrated in Figure 14. The procedure has the following steps: (1) twin shield tunnels are constructed injecting the isolated material during shield-driving first; (2) ground improvement is conducted considering the ground stabilization and the water tight for the following excavation, and seismically improvement; (3) excavation and withdrawing a part of the segments are conducted between those tunnels by the mining method; and (4) finally the body of the flat tunnel is constructed and the cavities between the excavated ground and the tunnel body is filled up with the same isolation material, improved ground or so at the intersecting area.

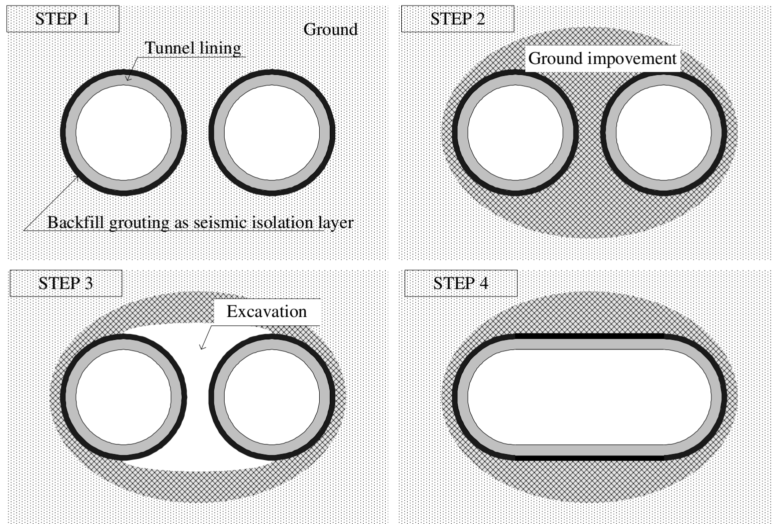


Figure 14: Conceptual procedure of real work for combination countermeasure of isolation layer and improved ground

As mentioned above, the work can be easily put into practice combining existing procedures. As well, it can be noticed that the method considering the seismic resistance is cost-effective by the meaning of utilizing ground improvement as a temporary work for excavation, if the economical isolation material for isolation layer is found out.

DISCUSSION OF NEW ISOLATION MATERIAL

The representative methods to increase seismic resistance of the shield tunnel in the longitudinal direction are introduced as follows: (1) making the tunnel body more flexible by setting flexible segments in the tunnel lining, installing the hard rubber in the joints of segments and so on; (2) installing the isolation layer around the surface of the tunnel to reduce the force transmitted from the ground; and (3)controlling damage mode by placing the weak point in a part of the tunnel body (JSCE, 2002).

Among these resistant methods, flexible segments and rubber joints have been usually used in Japan. On the other hand, isolation layer are adopted in the real construction work quite few as a reason of its inefficient cost although it is regarded as the most effective countermeasure considering Level-2 ground motion or necessitating taking the measure along the long span of the tunnel, which are the requirements of the ramp tunnel. So the authors attempt to develop new isolation material of low-cost using mixture material of granular rubber and the bond as an option of such material, which material have been used to elastic pavement or so. Where, considering adapting it to the isolation layer in real work, workability, durability and favor properties in environment are required in addition to the cyclic property for the isolation layer. Then the material is revised so as to adapt to those requirements. Hereafter the property of the new material is introduced.

The material is the mixture of granular rubber, which is made by cutting scraped rubber tires in pieces, and a polymer solution having the self-solidification property with time. Figure 15 presents the results of unconfined compression and extension tests for the material. The relations between cyclic shear modulus, damping ration, volume strain and shear strain by cyclic triaxial test are respectively shown in Figure 16,

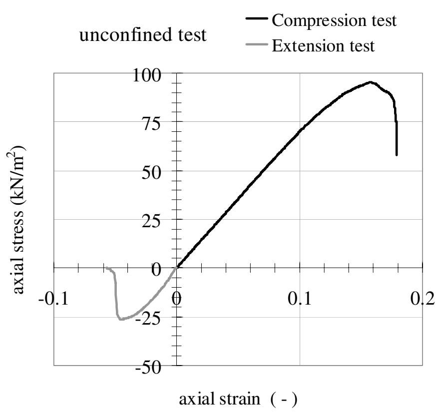


Figure 15: Relation of stress and strain of new material

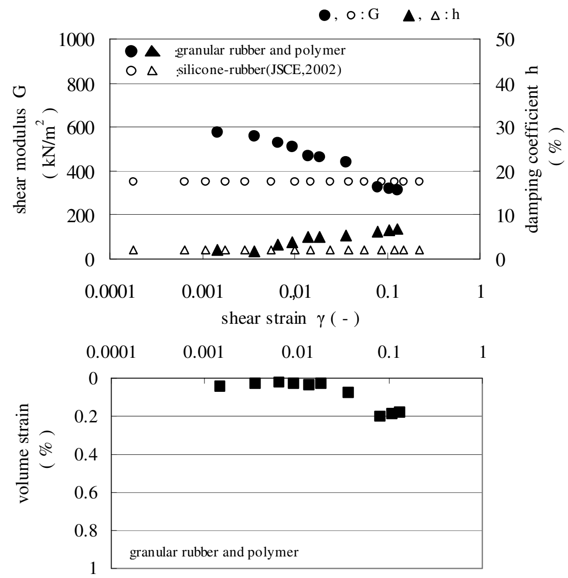


Figure 16: Cyclic property of new material

in which each volume strain was measured at ends of each shearing steps in drainage condition. Moreover, the property of the silicone-rubber as an existing isolation material (JSCE, 2002) is plotted either in Figure 16 in comparison.

From these figures, the trend of the shear modulus of the new material is globally similar to the silicone-rubber: that is, (1) the shear modulus is very small and the dependence on the shear strain level is low (seems to be almost independent); (2) the volume strain induced by cyclic shearing is negligibly small; and (3) the unconfined strength is low but the failure strain doesn't appear at least until enough large strain 20%. Above-mentioned property is suitable for the isolation layer of tunnels, so the material can be expected as the isolation material as far as such property while it is necessary to examine other requirements future.

CONCLUSIONS

This paper presents a new concept of the seismic countermeasure for a structurally special part of tunnel such as ramp of road tunnel and a crossover of double-truck railway tunnel, in which a flat and large cross-sectional tunnel and a junction of tunnels appear. Since seismically high stability is required for it, a series of centrifuge model tests of cross-sectional tunnel and ground system with following countermeasures were conducted in the transverse direction: isolation layer around outer surface of tunnel; ground improvement by cement-solidification surrounding tunnel; and combination of those ones.

As a result, the following findings about the seismic performance of flat cross-sectional tunnel in the transverse direction were obtained:

(1) The bending moment becomes greater at the sidewalls and the centers of slabs, and the axial force shows great value at the sidewalls at static condition. And the sectional forces become great at the corners at seismic condition.

(2) The anti-earthquake effectiveness of isolation-layer-measure seems to depend on the shear modulus ratio of the isolation layer and the surrounding ground as former studies. In the condition of this study,

it doesn't influence the behavior at static condition and the effectiveness is quite small at seismic condition.

(3) Ground-improvement-measure by solidification affects the reduction of the vertical and horizontal relative displacements of the tunnel at static and seismic condition respectively. But the sectional forces indicate a increasing trend, especially for the axial force of the sidewalls.

(4) The combination-measure of isolation layer and ground improvement reduce not only the deformation at static condition but also the sectional forces at static and seismic condition.

(5) Comparing to the sectional forces of dynamic and static loading, the forces coincide each other if the horizontal relative displacements are the same. It seems to be noticed that the kinematics interaction dominates the seismic behavior of the tunnel and the seismic deformation method in tunnel design are effective regardless of applying the countermeasures or not.

In addition, the applicability of the new material, which consists of granular rubber and polymer solution, as a seismic isolation layer was examined about the cyclic property. The result is similar to the existing material. Therefore, the new material can be respected as a cost-effective alternative for seismic isolation layer considering Level-2 ground motion with respect to the structurally special part of tunnel such as ramp tunnel.

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REFERENCES

N.Ohbo, K.Horikoshi, T.Yamada, K.Tachibana, and H.Akiba: "Dynamic Behavior of a Underground Motorway Junction due to large Earthquake", Paper submitted to 13th World Conference on Earthquake Engineering, 2004.

A.Takahashi, J.Takemura, A.Suzuki and O.Kusakabe: "Development and Performance of an Active Type Shear Box in a Centrifuge",International Journal of Phisical Modelling in Geotechnics,Vol.1,No.2,2001.

T.Yamada, H.Nagatani, H.Igarashi, and A.Takahashi: "Centirifuge model tests on circular and rectangular tunnels subjected to large earthquake-induced deformation", Proceedings of 3th International Symposium of Geotechnical Aspects of Underground Construction in Soft Ground, 2002.

H.Zhi, H.Otsuka, and S.Toyonaga: "Isolation Analysis of Underground Structure", Memories of the Faculty of Engineering, Kyushu Univ. Vol.59, No.1, pp.21-29, 1993.

Japanese Society of Civil Engineers: "Guideline for Seismic Isolation and Response Control ", 2002. (in Japanese)

T.Suzuki: "The Axisymmetric Finite Element Model developed as a Measure to evaluate Earthquake Responses of seismically isolated Tunnels", Proceedings of 12th World Conference on Earthquake Engineering, 2000.