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EXPERIMENTAL STUDY OF SEISMIC BEHAVIOR OF BOX TYPE TUNNEL CONSTRUCTED BY OPEN CUTTING METHOD

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SUMMARY

In order to investigate the seismic behavior of cut-and-cover tunnel, several model shaking table tests and numerical analyses were carried out. In the shaking table test, separation and slipping between the structure and soil were taken into consideration. In the numerical analyses, two typical methods, such as a two dimensional dynamic analysis and a static frame analysis with the seismic deformation method were used. Based on these results, external forces the structure was subjected to were made clear. The effect of the separation and slipping was not significantly important for the dynamic response of structure. The mechanism of separation and slipping could be explained by the relation between the total shear force of structure and the distribution of shear stresses and the normal pressures all around the exterior surface of the tunnel. The analytical methods used in seismic design were checked by the experimental results that didn't consider separation or slipping. The dynamic analysis results showed good agreement with the experimental results. The seismic deformation method showed a little conservative value. It was made clear that this static analysis was easier to use than the dynamic analysis for designing the conventional tunnel constructed by the open cutting method.

INTRODUCTION

The Hyogoken-Nambu earthquake on January 17, 1995 caused severe damage to various structures. The damage to cut and cover tunnels of subways especially drew attention because underground structures had been considered relatively safe from earthquake effects when compared with structures above the ground. In most cases, except for important facilities and those constructed in soft subsoil, seismic resistant design had not been considered. Its design method was not the one intended for such large earthquakes as the above. From this viewpoint, a new seismic design method has been desired for cut and cover tunnels against larger earthquakes.

External forces the structure is subjected to are in the form of shear stresses and normal pressures all around the exterior surfaces of the tunnel. When we consider such a larger earthquake as the Hyogoken-Nambu earthquake, separation and slipping between the tunnel and soil will occur. It's very important to study the influence of the separation and slipping on the external force to the tunnel and its dynamic response. The external forces have been experimentally and analytically studied by several researchers [e.g. Watanabe, 1991], but the influence of the separation and slipping on the external forces has not been studied much. Here we conduct shaking table tests taking into consideration the effect of artificial separation and slipping.

On the other hand, the response of structure during earthquake has to be calculated rationally in seismic design. Many analytical methods have been proposed in research papers and design codes [e.g. Tateishi, 1992 and Railway Technical Research Institute, 1999]. In these studies, the applicability of dynamic response analysis has been checked by using experimental results. But static analysis, which is a useful method for design, has been checked not by experimental results but by dynamic analysis results. So, we check the applicability of static analysis with the seismic deformation method based on the shaking table tests results.

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Table 1 Experiment cases

Case	Tunnel	Condition of separation and slipping	
1	2-span		none
2			ceiling and sidewalls
3	3-span		none
4			ceiling and sidewalls
5			ceiling only

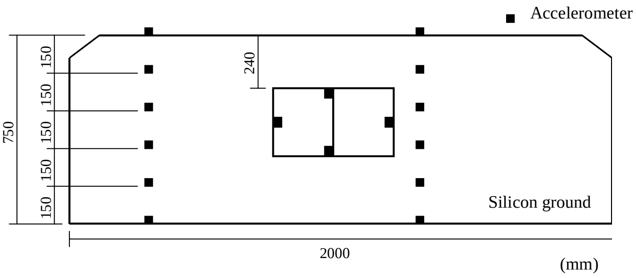


Fig. 1 Model ground and accelerometers

In this paper, we report the results of shaking table tests of cut-and-cover tunnel in a silicon ground and study the external forces on the tunnel. Artificial separation and slipping is set then on the external surface of the model tunnel and a shaking table test is performed again. The distributions of external force of shear stresses and normal pressures are studied and the effect of separation and slipping is researched. Analytical simulations are conducted by dynamic response analysis with the two-dimensional finite element method and static frame analysis with the seismic deformation method. The experimental results and the applicability of these methods are checked. Parametric studies are also performed to cover another case different from the experiment.

MODEL SHAKING TABLE TESTS

Outline of model shaking table tests

Two- and three-span rectangular tunnel models were installed in the model ground. In order to investigate the external forces that a structure receives during an earthquake and get a fundamental data to check the applicability of analytical method, shaking table tests were carried out. Shear stresses and normal pressures were measured simultaneously by two-direction loadcells, and horizontal and vertical accelerations were measured by accelerometers installed in the ground and on the tunnel model. The strain in the middle wall was measured by strain gages placed on the front and back of the middle wall.

Experimental cases are shown in Table 1. There are five cases with different separation and slipping conditions and model tunnels, of which the first 2 cases are mainly reported in this paper. In this experiment, a case where the stiffness of structure was smaller than that of ground was researched. The other case where the stiffness of structure was larger than that of ground was researched by numerical analysis.

Model ground and model tunnel

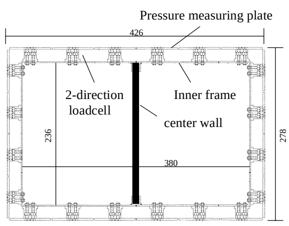


Fig. 2 Model tunnel (two-span)

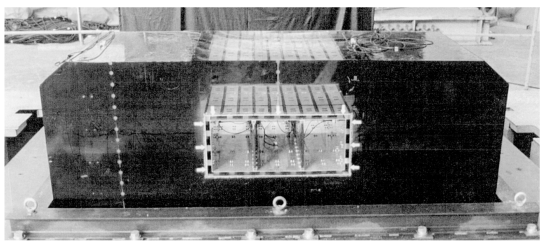


Fig. 3 Model ground and model tunnel (three-span)

Table 2 Properties of ground

	Real ground	Model ground
Shear modulus kN/m^2 j	37500	120
Unit weight kN/m^3 j	18	10
Poisson's ratio	0.40	0.50
Depth of subsoil(m)	18.75	0.75

Fig. 1 shows a general view of model ground. The model ground was made of silicon based on the similarity law to consider the clay of N-value 5, whose thickness of ground surface layer was 18.75m and the overburden depth was 6.0m. Properties of the model ground are shown in Table 2. As shown in Fig.2, the tunnel model consisted of two-direction loadcells to measure the subgrade reaction of shear stresses and normal pressures, inner frame and pressure measuring plate, which were made of aluminum. 20 two-direction load-cells were installed in total in the 2-span tunnel model. The center wall was made of hard rubber with a thickness of 10 mm. In total, 28 pieces of strain gages were set at the front and back both on the right and left sides of the center wall. To prevent the influence of the surface boundary, external forces to the tunnel were measured at the middle section (30cm) of the tunnel in the direction of depth, and dummy plates were installed at other sections (20cm each).

To consider the separation and slipping between the model tunnel and the model ground in Case 2. Teflon-sheets, of which the coefficient of friction was 0.05, were inserted between the model ground and the exterior surface of the ceiling slab and sidewalls. In Case 1 without the Teflon-sheets, the silicon ground adhered to the tunnel by its adhesive strength. But in Case 2 with the Teflon-sheets, not only slipping but also separation was considerable as the adhesion between the silicon ground and the model tunnel was cut. An equivalent shear modulus of the two-span model tunnel was 34 kN/m^2 and that of the three-span tunnel was 41 kN/m^2, which were obtained by a lateral loading tests of the model tunnels. The model tunnels were more flexible than the model ground, of which the shear modulus was 120 kN/m^2.

Natural frequency of the model ground

A resonance examination was carried out to grasp the first natural frequency of the model ground. The damping ratio of the model ground was calculated from the free the damping vibration wave profile. As a result, the first natural frequency of the model ground was 3.7 Hz and the damping ratio was 2.5 %. In Case 2 with the Teflon-sheets, when the strong motion was applied and the behavior between the model ground and the model tunnel showed strong non-linearity, the frequency characteristics of the model would change slightly. As the response of the model wasn't sensitively affected by the changes in the frequency of the model, a 4.0 Hz sinusoidal wave (50gal) that was slightly shifted from the natural frequency of the model was used as an input motion.

Distribution of acceleration

Fig. 4 shows the distribution of acceleration when the relative displacement of the tunnel between the ceiling slab and bottom slab was the biggest. Case 2 with the Teflon-sheets showed 20 to 30 percent smaller accelerations than Case 1 without Teflon-sheets. When the separation and slipping occurred, the equivalent shear modulus of tunnel would be smaller and the frequency characteristics of the model would also be smaller. It was thought that the amplification characteristics of the model shifted to the smaller side of frequency and the acceleration of ground would be smaller. But the relative accelerations of ground between the ceiling slab and bottom slab were almost the same. This means that relative displacements of

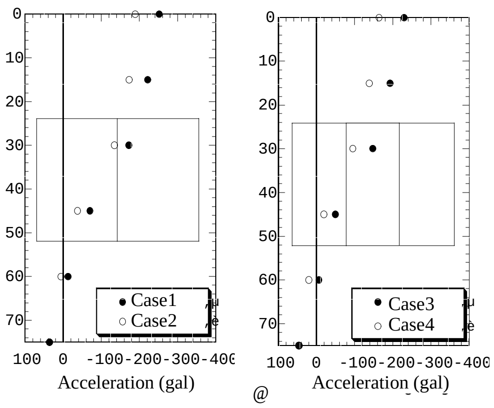


Fig. 4 Response acceleration of ground far from the model tunnel

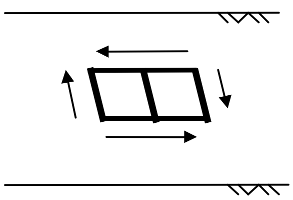
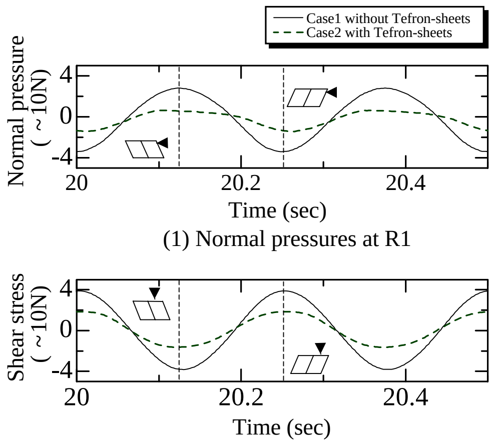


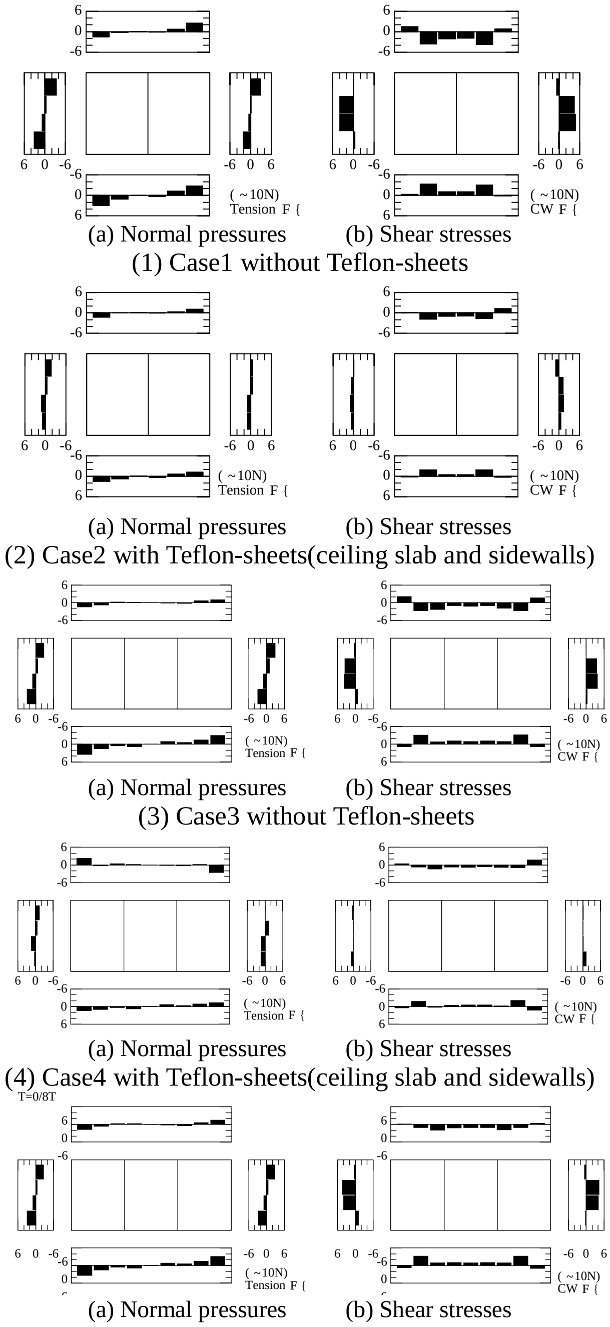
Fig. 6 Direction of shear stresses on tunnel



(1) Normal pressures at R1

(2) Shear stress at U2

Fig. 7 Time history of external forces



(a) Normal pressures (b) Shear stresses

(1) Case1 without Teflon-sheets

(a) Normal pressures (b) Shear stresses

(2) Case2 with Teflon-sheets(ceiling slab and sidewalls)

(a) Normal pressures (b) Shear stresses

(3) Case3 without Teflon-sheets

(a) Normal pressures (b) Shear stresses

(4) Case4 with Teflon-sheets(ceiling slab and sidewalls)

(a) Normal pressures (b) Shear stresses

(5) Case5 with Teflon-sheets(ceiling slab only)

Fig. 5 Distribution of external forces

tunnel and ground were also almost the same. The effect of absolute accelerations of tunnel to the dynamic response was thought to be small according to the previous studies. The acceleration of the model tunnel was changed, but the total external forces to the model tunnel would be almost the same with that in Case1 and Case 2. The results of Case3 and Case4 for the three-span tunnel show the same tendency.

The relative displacements of tunnel between the ceiling and bottom slab were calculated by accelerations measured at the top and bottom of tunnel. The relative displacement of Case 1 was 0.27cm and that of Case2 was 0.26cm. The difference was just only 4 percent. For Case 3, Case4 and Case5, the relative displacement was 0.24, 0.23 and 0.24cm, respectively.

External forces on the model tunnel

Shear stresses on the model tunnel

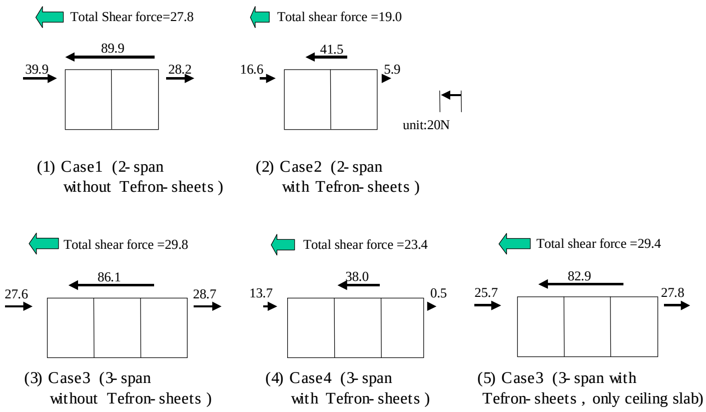


Fig. 8 Totalshear force

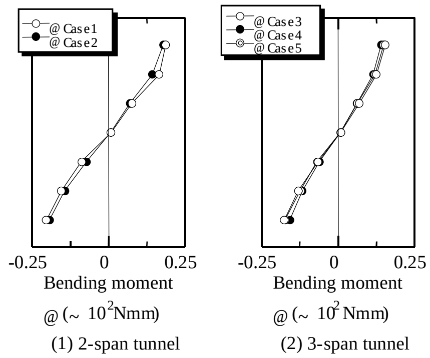


Fig. 9 Bending moment of center wall

The distribution of Shear stresses on the model tunnel is shown in Fig.5 when the model tunnel was deformed to the left side as shown in Fig.6. The positive value means that the shear stresses act in the clockwise direction. When the ground is deformed to the left side, shear stresses are thought to act on the tunnel in the direction shown in Fig. 6. As shown in Fig. 5, the direction of shear stresses measured in the experiment was similar to that in Fig. 6 except for that measured at the corner of ceiling slab. As for the direction of shear stresses turning over at the corner of ceiling slab, it was thought that the shear stresses were influenced by the normal pressures occurred in the upper part of sidewall. In this case, the tunnel was more flexible than the ground and the structure tended to be deformed more than the ground. So at the top corner of left wall, normal pressures of compression occurred to reduce the deformation of tunnel as described later. In contrast, normal pressures of tension occurred at the top of right wall. The ground is a continuous material and shear stresses at the corners of slab and the normal pressures at the top of sidewall are interacted with each other. It was thought that the shear stresses at the corner of slab acted to reduce the deformation of model tunnel, too.

The shear stresses in Case 2 with the Teflon-sheets were smaller than those in Case 1 without the Teflon-sheets. Fig.7 shows time histories of the shear stress at U2, which is the center of the right span of ceiling slab. The time history of Case 2 with Teflon-sheets showed a lower and flat peak value. A slipping was thought to have occurred. It is thought that when the separation and slipping occur during a strong earthquake, the shear stresses the tunnel is subjected to will decrease.

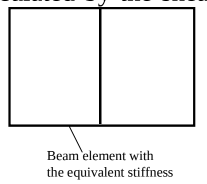
Normal pressures on the model tunnel

The distribution of normal pressures on the model tunnel is shown in Fig.5 when the model tunnel was deformed to the left side as shown in Fig.6. The positive value means tension. A compressive normal pressure occurs at the top of left wall. The direction of normal pressures at the sidewall changed into the upper and lower sides. The normal pressures in Case 2 with the Teflon-sheets were smaller than those without the Teflon-sheets like the shear stresses. Especially, the normal pressures at the corner of sidewalls and slabs were much smaller. It was thought that the normal pressures at the upper part of both sidewalls were part of reaction forces, which correspond to the shear stresses at the ceiling slab. When the Teflon-sheets were inserted between the tunnel and the ground, the shear stresses at the ceiling slab decreased and normal pressures at the sidewall also decreased.

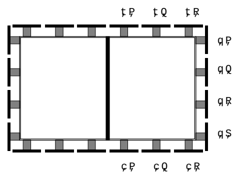
Time histories of normal pressure at the upper side of the right wall are shown in Fig.7. Judging from the flat and lower shape of time history around 20.12 sec when the model tunnel deformed to the left side, it was thought a separation occurred at that point. In contrast, in the time history around 20.25sec when the tunnel was deformed to the right side, there was a compressive pressure with no flat peaks. Hence, at the upper part of sidewall where the model tunnel apart from the ground, normal pressures of tension could occur and the smaller shear stresses could deform the model tunnel easily.

Total shear force

The total lateral force that the tunnel is subjected to is called a total shear force. The total shear force is calculated by the shear stresses at the ceiling slab and the normal pressure at the upper part of both sidewalls.

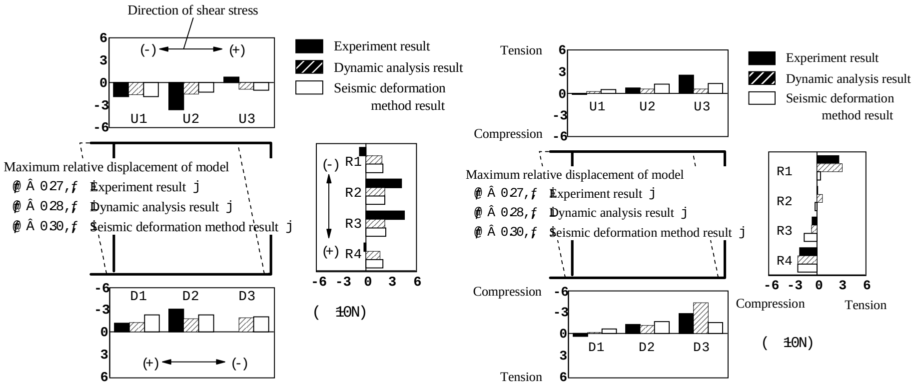


(1) Simplified model



(2) Detail model

Fig. 10 Analytical model



(1) Shear stresses

(2) Normal pressures

Fig. 11 Distribution of external forces

The total shear forces are shown in Fig.8. In Case 1 without the Teflon-sheets, the shear force at the ceiling slab was larger and the normal pressure at the slab, which was thought to be one of the reaction forces against the shear force, was also larger. In Case 2 with the Teflon-sheets, shear force at the ceiling slab was smaller and the normal pressure at the slab was also smaller. Finally, the total shear forces of Case 1 and 2 with/without Teflon-sheets were almost same. This was the same results for Case 3 to Case 5.

Bending moment

The bending moment of the center wall is shown in Fig.4. The bending moment corresponds to the relative displacement of tunnel. In Case 2 with the Teflon-sheets, the bending moment showed a smaller value and it was just a few percent. The reason was that when separation and slipping occurred, the distribution of shear stresses and normal pressures changed but the total shear forces of structure were almost the same value. There were no dominant differences in the total shear force and the dynamic response of structure was almost same.

2.8 Effect of separation and slipping

Based on these results, it was concluded that the effect of separation and slipping to the dynamic response of tunnel was small when the tunnel was flexible than ground. This was the same results with our analytical study [Nishiyama et al., 1999]. On the other, we also conducted the same study for the case when a tunnel was stiffer than ground and concluded that the effect of separation and slipping was not so big even in another case.

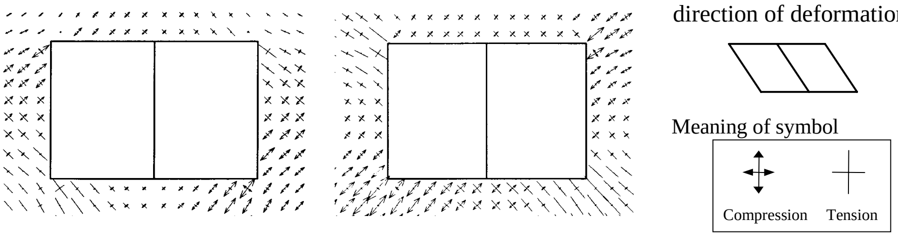
ANALYTICAL SIMULATION USING DYNAMIC ANALYSIS

Condition of analysis

A numerical simulation for experiment results was conducted with the dynamic analysis code FLUSH. Based on the properties of silicon obtained in laboratory tests, the properties of ground used for the simulation were arranged so that the natural frequency of the ground model was equal to that of the experiment. It was complicated in the FEM analysis to make a detail tunnel model such as the section shown in Fig.10. A simplified tunnel model, which had an axis following the surface of pressure measuring plate and the equivalent stiffness to the experiment tunnel, was adopted. The flexural rigidity was adjusted to simulate the lateral loading test of the tunnel model. It was thought that the external forces to the tunnel could be grasped by using the simplified tunnel model with the equivalent stiffness.

Analytical results

Distributions of accelerations at the tunnel and ground showed good agreement with the experiment results.



(1) 1EI (tunnel is more flexible) (2) 100EI (tunnel is stiffer)

Fig. 12 Principal stresses around the model tunnel

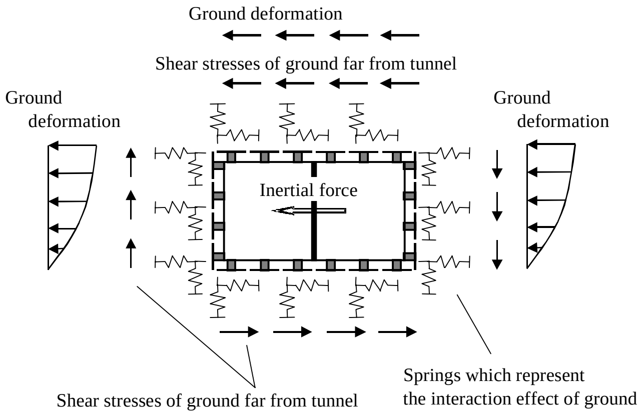


Fig. 13 Concept of the seismic deformation method

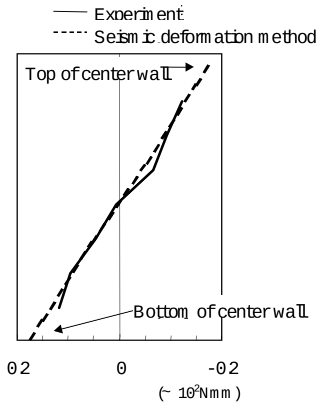


Fig. 14 Bending moment

This means that the properties used in analysis were proper. The external forces of analytical results are shown in Fig.11 together with experimental results. The external forces were calculated by multiplying the stress of soil element in contact with the beam element by the area of a pressure measuring plate. As for the shear stresses, there were some differences at sidewalls and especially at their corners. This might be the reason that the real model tunnel had pressure-measuring plates that were separated from each other, but the analytical model tunnel has a continuous pressure measuring plate. But, the total shear stresses of ceiling slab and that of bottom slab and sidewalls were the almost same with those of the experiment. The normal pressures generally agreed with the experiment results. The maximum relative displacement of tunnel model also agreed with the experiment results. Based on these results, applicability of static frame analysis with seismic deformation method was verified.

Effect of shear stiffness ratio of soil and tunnel

Fig.12 shows the principal stress of the ground near the tunnel model when relative displacement of tunnel is the largest. Fig.12(1) shows the result the equivalent stiffness (EI) of the tunnel model was used and (2) shows that of 100 times EI. When the member stiffness was smaller, it was identified that a normal pressure of compression occurs at the top of the left wall to reduce deformation. On the other hand, when the member stiffness was larger, a normal pressure of tension occurred at the top of the left wall to increase deformation. Hence, the direction of the normal pressure occurring at the sidewall changed according to the relation of stiffness between ground and tunnel. In other words, when stiffness of structure was smaller than that of the ground, subsoil reaction occurs to prevent deformation because the structure deforms more than the ground by external forces. On the other hand, when the stiffness of structure was larger than that of the ground, subsoil reaction occurred to increase deformation, because structures with larger stiffness deformed less than the ground.

ANALYTICAL SIMULATION USING THE SEISMIC DEFORMATION METHOD

Condition of analysis

Analytical simulation by the seismic deformation method is used to check its quantitative applicability to seismic design. In the seismic deformation method, a detailed tunnel model was adopted as shown in Fig.10 (2). The inner frame, load cells and pressure-measuring plates were modeled with beam elements. The ground was modeled with spring elements, which were set all around the exterior surfaces of the tunnel. There were several methods to estimate the spring coefficient such as FEM, simplified formulas adopted in design codes [e.g. Railway Technical Research Institute, 1999]. The simplified formula was used taking into consideration the design procedure. Loads used to analysis were calculated based on the experiment results of ground motion. The relative deformation of ground was calculated by integrating accelerations of ground. The maximum relative ground deformation between ceiling and bottom slabs was 0.238cm. The shear stresses of ground were calculated by multiplying the mean shear distortion, which was calculated from the relative displacement between slabs, by the shear modulus of model ground. The inertia force of model tunnel was calculated from the acceleration of ground at the same depth as that of the tunnel.

Analytical results from seismic deformation methods

As shown in Fig.11, the relative displacement of tunnel and the distribution of shear stresses and normal pressures were similar to those of the experiment. Even though there were slight differences in response values measured at corners, others generally agreed with the experiment results. The total shear stresses of ceiling slab and that of bottom slab and sidewalls were the almost same with those of the experiment. The bending moment of the center wall also agreed with the experiment results as shown in Fig.14. Based on these results, applicability of static frame analysis with seismic deformation method was verified.

CONCLUSION

In order to investigate the seismic behavior of a cut-and-cover tunnel, several model shaking table tests and numerical analyses were carried out. In the shaking table tests, a separation and slipping between the structure and soil was taken into consideration. In numerical analyses, two typical methods, such as two-dimensional dynamic analysis and static frame analysis were used by the seismic deformation method. On the basis of these results, the following can be concluded when the tunnel is flexible than ground.

The external forces the structure was subjected to were made clear. The effect of the separation and slipping were not significantly important for dynamic response of structure. The mechanism of the separation and slipping can be explained by the relation between the total shear force of structure and the distribution of shear stresses and normal pressures all around the exterior surfaces of the tunnel. The dynamic analysis showed good agreement with the experimental results and the seismic deformation method showed a little conservative value. It was clear that this static design procedure was easier to use than the dynamic method for designing conventional tunnels constructed by the open-cutting method.

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