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# Study on seismic behavior and seismic design methods in transverse direction of shield tunnels

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**Abstract.** In order to investigate the seismic behavior and seismic design methods in the transverse direction of a shield tunnel, a series of model shaking table tests and a two-dimensional finite element dynamic analysis on the tests are carried out. Two kinds of static analytical methods based on ground-tunnel composite finite element model and beam-spring element model are proposed, and the validity of the static analyses is verified by model shaking table tests. The investigation concerns the dynamic response behavior of a tunnel and the ground, the interaction between the tunnel and ground, and an evaluation of different seismic design methods. Results of the investigation indicate that the shield tunnel follows the surrounding ground in displacement and dynamic characteristics in the transverse direction; also, the static analytical methods proposed by the authors can be used directly as the seismic design methods in the transverse direction of a shield tunnel.

**Key words:** seismic behavior; seismic structural design; shield tunnels; shaking table testing; seismic deformation method.

## 1. Introduction

Shield tunnels are utilized widely in lifeline construction in urban areas of Japan, China and many other countries. However, some areas are located in high earthquake intensity regions in these countries and have encountered frequent seismic activity in the past. Seismic damage of the shield tunnels was reported from the 1985 Mexico Earthquake and the 1995 Hyogoken-Nanbu Earthquake (Tamura 1986 and JSCE 1996). Now, seismic design has become an important topic in the construction of shield tunnels. In the seismic design of shield tunnels, in which the analyses are focused on the longitudinal direction of the tunnel and the surrounding ground (JSCE 1996), generally it is thought that this design philosophy is suitable for circular shield tunnels of mid-sized outer diameter or smaller. Shield tunnels with complex cross sections or large-scale cross sections are increasing in number recently, and more and more seismic design cases in the transverse direction are required. However, since the dynamic interaction between shield tunnels and the surrounding ground is very complex, a practical analytical method suited to seismic design in the transverse direction of the shield tunnels has not been developed.

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Engineers and researchers have concentrated on the development of practical seismic design methods in the transverse direction of shield tunnels in the last decade. Generally, a two or three-dimensional dynamic analysis using a soil-structure composite model can be employed when investigating dynamic characteristics in the transverse direction of shield tunnels. But in dynamic analysis, input and output data are enormous, and the interpretation of analytical results is very complex, as no practical seismic design method can be utilized widely. The seismic deformation method, a static analytical method in which response displacements of free ground are considered as seismic forces acting on the structures of the tunnels, has been suggested by PWRI (1977) and JSCE (1996) as a practical seismic design method in the longitudinal direction of shield tunnels. Based on the concept of the seismic deformation method, theoretical solutions were suggested to approximately evaluate the maximum sectional forces on shield tunnels in the transverse direction under ground motion (Shiba 1991 and PWRI 1992). However, dynamic characteristics in the transverse direction of such shield tunnels have not been clarified; moreover the suggested theoretical solutions can not be used directly in shield tunnels located in irregular ground. in order to make a thorough investigation of such the seismic behavior, including the interaction between shield tunnels and surrounding ground, and developing rational and practical seismic design methods in the transverse direction of shield tunnels, a series of model shaking table tests was carried out. In addition, static and dynamic analyses on these tests and an evaluation of different seismic design methods were performed in this study.

## 2. Model shaking table tests

### *2.1 Prototype and test model of tunnel and ground*

A double track subway shield tunnel whose outer diameter is 10.0 m is considered as the test prototype. The segment of the shield tunnel is a reinforced concrete flat plate type of 1 m width and 0.4 m thickness. It is assumed that the shield tunnel is located on a poor alluvium (blow count using Standard Penetration Test is less than 3), and the thickness of the alluvium and the overburden of the shield tunnel is set to 30 m and 14 m respectively. The base of the ground is located on a very hard diluvium (Standard Penetration Test blow count is greater than 50) which can be considered as a rigid body in the seismic design.

In the model shaking table tests, materials for the ground and tunnel were chosen according to the similarity law. The scale factor of the physical quantity was introduced on the assumption that the inertial force and the elastic force in the ground are of a mutually independent dominant physical quantities. The scale factors for physical quantities is shown in Table 1.

The poor alluvium and the shield tunnel were simulated by silicone rubber and polyethylene respectively. In order to facilitate the manufacturing of the tunnel model, transverse and circumferential joints of segments were neglected. Moreover, the tunnel model was divided into 7 mutually independent rings whose intervals were filled by soft synthetic-rubber rings, so that the influence of longitudinal ground boundaries on the central section of the model could be reduced as much as possible. The ground model, whose width is 900 mm, was considered to have free boundaries at the sides. According to prior preliminary dynamic analyses, in cases where the width of the ground model is larger than 900 mm, the vibration characteristics of the central position of the ground model change little in comparison with semi-infinite side boundaries, even if the sides of

Table 1 Scale factor

| Items | Length | Time | Density | Strain | Elastic modulus | Acceleration |
|---|---|---|---|---|---|---|
| Formula | $\frac{l_m}{l_p}=\lambda$ | $\frac{t_m}{t_p}=\tau$ | $\frac{\rho_m}{\rho_p}=\tau$ | $\frac{\varepsilon_m}{\varepsilon_p}$ | $\frac{E_m}{E_p}=\frac{\gamma\lambda^2}{\tau^2}$ | $\frac{a_m}{a_p}=\frac{\lambda}{\tau^2}$ |
| Value | 1/100 | 1/10 | 1/1.8 | 1/1 | 1/180 | 1/1 |

Note: The subscript $m$ denotes the test model, the subscript $p$ denotes the prototype.

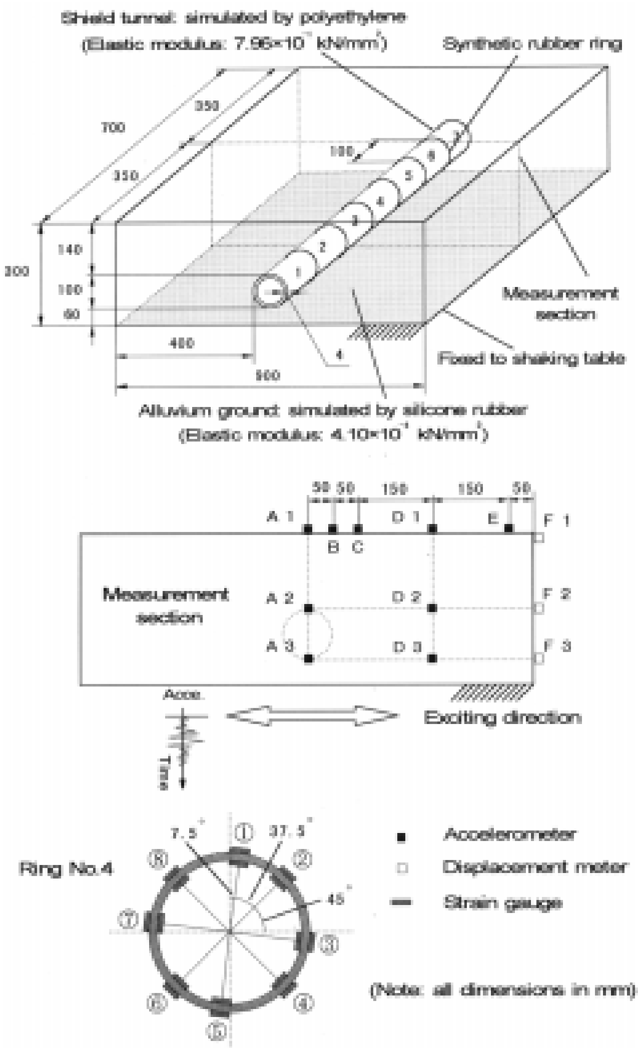



Fig. 1 Details of test model and measurement points

the ground model are treated as free boundaries. Details of the test model and measurement points are shown in Fig. 1.

### *2.2 Outline of tests*

All measurement sensors were installed in the central section of the test models. Accelerometers, which record the time history of the absolute acceleration, were put on the shaking table, the ground surface and the underground respectively. Strain gauges, which record the time history of the strain, were put on cross-sections of the tunnel; moreover, the bending strain component and the axial strain component of each cross section were measured respectively. Laser displacement meters, which record the time history of the horizontal displacement, were put on one side of the ground.

Model shaking table tests were carried out for both the free ground model and the ground-tunnel composite model. The bottoms of the test models were fixed to the shaking table, and a unidirectional horizontal exciting wave was input from the shaking table in the transverse direction. The tests were carried out as follows: first, the model was excited by a sinusoidal wave in which the acceleration amplitude was set to 80 gal and the frequency was changed from 2 Hz to 50 Hz. Subsequently, records from the Tokachi-Oki Earthquake, the El-Centro Earthquake and the Hyogo-Ken Nanbu Earthquake were used as the exciting waves respectively, with their time base being shortened to 1/10 in real time and the maximum acceleration set to 300gal. All tests were carried out within the elastic range and sliding displacements between the tunnel and the ground did not occur.

## 3. Numerical analysis methods

### *3.1 Dynamic finite element analysis*

In order to explain the test phenomena and verify the usefulness of dynamic analysis in the seismic design, a two-dimensional dynamic finite element analysis was carried out on the model shaking table tests (both the free ground model and the ground-tunnel composite model). The central full section of the test model, which can be considered as the state of the plane strain, was set as the objective section of the analysis. The ground and the tunnel were modeled by using isoparametric solid elements and beam elements respectively, and it is assumed that sliding displacement between the tunnel and ground does not occur. To simulate the boundary condition of the test model, the base was considered as a rigid body and the sides of the ground as free boundaries. In the analysis, the time history complex response method was employed (JSCE 1989). The finite element idealization of free ground in the numerical model is shown in Fig. 2, and that of the ground-tunnel composite in the numerical model is shown in Fig. 3. The damping constant of the ground was calculated by using the resonance curves of the ground acceleration that had been measured in tests. Because the weight of the tunnel is much less than that of the ground dug out, damping of the tunnel was disregarded in the analysis. The time history of the acceleration, which had been measured from the shaking table in the tests, was input from the bottom of the ground.

### *3.2 Static analysis based on seismic deformation method*

#### *3.2.1 Static analysis using ground-tunnel composite finite element model*

On the basis of the concept of the seismic deformation method, a two-dimensional static analysis using the ground-tunnel composite finite element model was proposed. In this analysis, the modeling of the ground and the tunnel is the same as that of the finite element dynamic analysis,

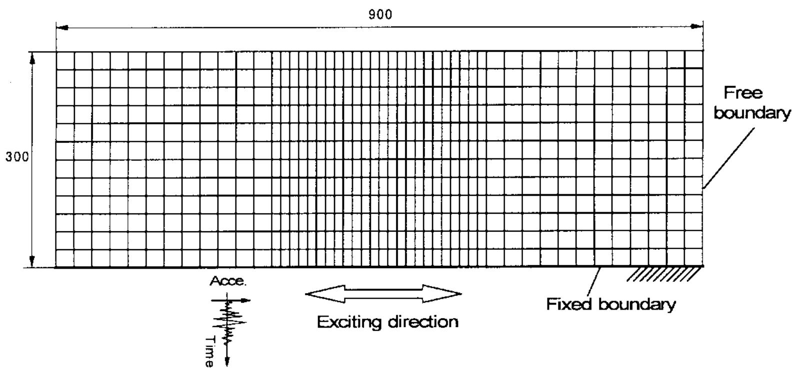



Fig. 2 The finite element idealization of free ground in dynamic numerical model

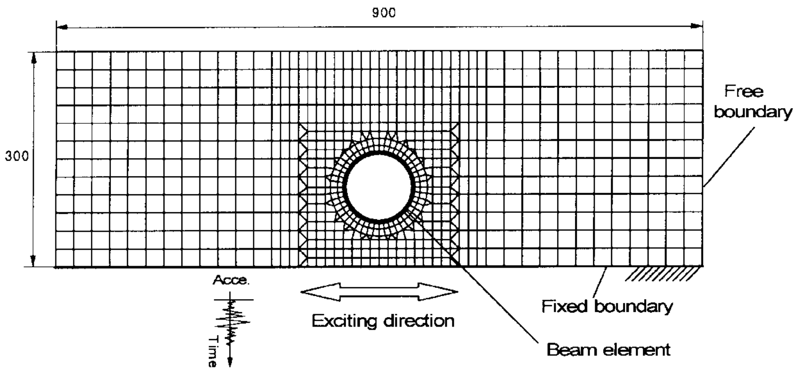



Fig. 3 The finite element idealization of ground-tunnel composite in dynamic numerical model

but only a part of the full test section was needed; moreover the level roller supports were installed in the side boundaries of the ground. The relative displacements of the free ground employed as seismic forces, which can be calculated easily using the above two-dimensional dynamic analysis on the free ground or one-dimensional approximate dynamic analysis in which the sides of the ground can be treated as semi-infinite boundaries, were input statically through the side nodes of the ground boundaries. Because, in the viewpoint of the design, the maximum sectional forces of tunnel are of great significance, the time when the largest displacement difference between the top and bottom of the tunnel occurred was only set in the analysis. The finite element idealization of the ground-tunnel composite is shown in Fig. 4.

### *3.2.2 Static analysis using beam-spring element model*

The tunnel was estimated by beam elements and the interaction between ground and tunnel was estimated by radial ground spring elements and tangential ground spring elements (Murakami and Koizumi 1980). Seismic forces due to the relative displacements and shear stresses of the free ground, which were calculated using the one-dimensional or two-dimensional dynamic analysis on the free ground, are employed in the analysis. The displacements of the free ground were input statically through the ground springs. In the meantime, the ground shear stresses were directly input through beam nodes statically. Like the above static ground-tunnel composite finite analysis, the time

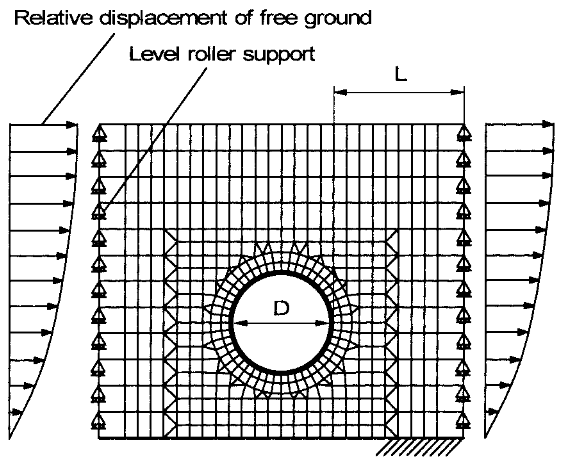



Fig. 4 Static analysis using ground-tunnel composite finite element model

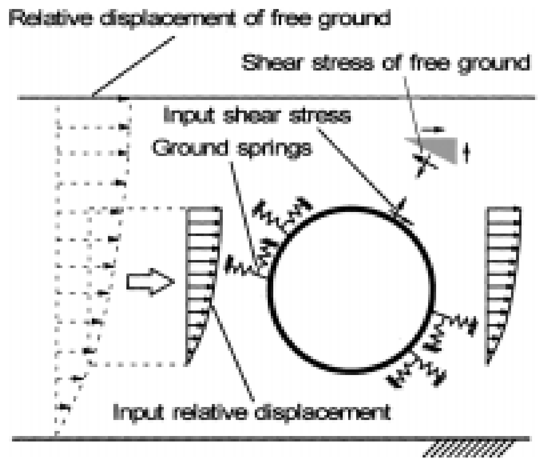



Fig. 5 Static analysis using beam-spring element model

when the largest displacement difference between the top and bottom of the tunnel occurred was only set in the analysis. The analytical model of the shield tunnel is shown in Fig. 5.

## 4. Dynamic behavior of the tunnel and ground under seismic motion

Based on results of the shaking table tests and dynamic analyses of the tests, the dynamic behavior of the tunnel and ground under seismic motion were achieved as follows.

The resonance curves of ground accelerations and the resonance curves of ground relative displacements are shown in Fig. 6 and Fig. 7 respectively. The vibrational modes of ground accelerations and relative displacements under the sinusoidal excitation are shown in Fig. 8 and Fig. 9 respectively. From these figures, it can be observed that the resonance curves of ground accelerations and the resonance curves of ground relative displacements as well as the vibrational modes change little or not at all, even if a shield tunnel is constructed in the ground. Also, from the resonance curves of bending and axial strains of the tunnel that are shown in Fig. 10 and Fig. 11 respectively, it can be observed that the resonant frequency of strains of the tunnel is the same as

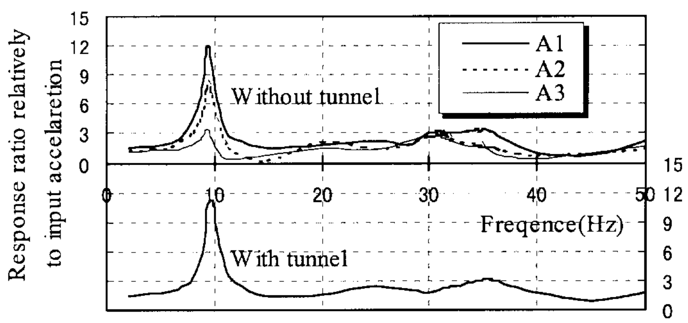



Fig. 6 Resonance curves of ground accelerations (based on tests)

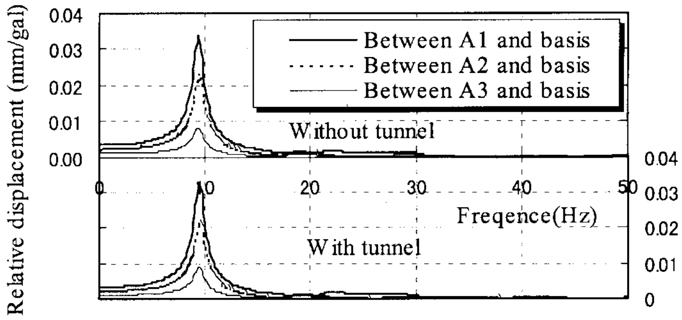



Fig. 7 Resonance curves of ground relative displacements (based on dynamic analysis)

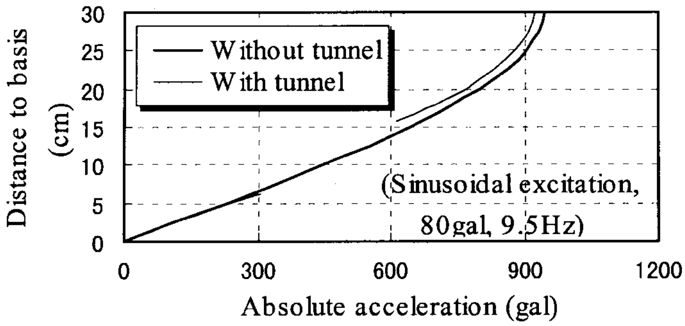



Fig. 8 Vibrational mode of accelerations in central ground (based on dynamic analysis)

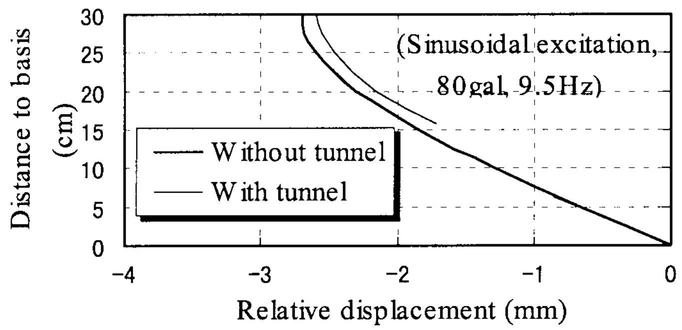



Fig. 9 Vibrational mode of relative displacements in central ground (based on dynamic analysis)

that of accelerations and relative displacements of the ground. One can confirm that self-oscillation of the shield tunnel does not occur under seismic motion and the shield tunnel entirely follows the surrounding ground in dynamic behavior.

Moreover, the comparison between waveshapes of the bending strain of the tunnel and waveshapes of the ground acceleration is shown in Fig. 12, while the comparison between waveshapes of the bending strain of the tunnel and waveshapes of relative ground displacement is shown in Fig. 13 (only taking the Tokachi-Oki Earthquake excitation, section ② of the tunnel as an example). It can be observed that the waveshapes of the bending strain of the tunnel are more similar to those of the relative ground displacement than the ground acceleration. Therefore, it can be confirmed that

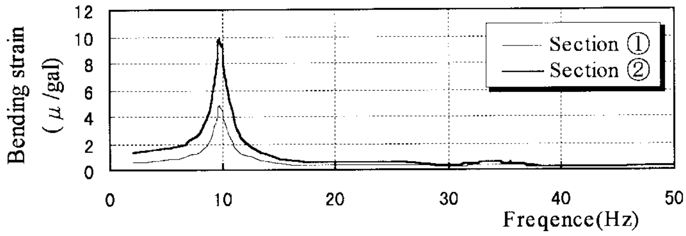



Fig. 10 Resonance curves of bending strains of the tunnel (based on tests)

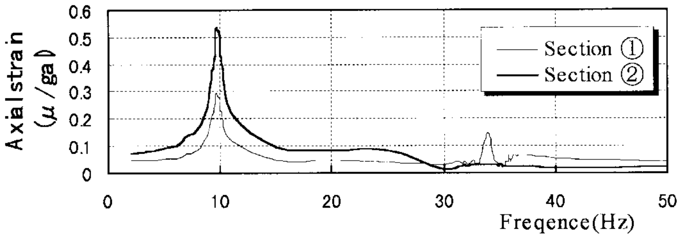



Fig. 11 Resonance curves of axial strains of the tunnel (based on tests)

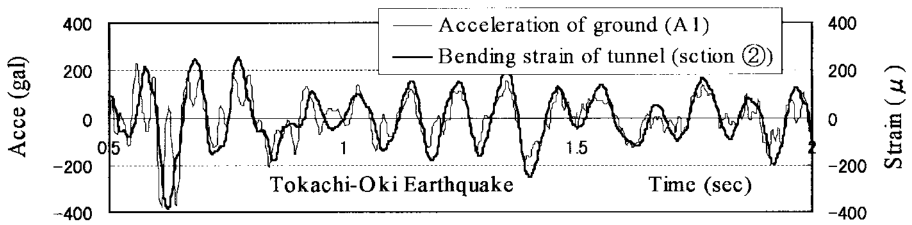



Fig. 12 Comparison between waveshapes of ground acceleration and waveshapes of tunnel strain

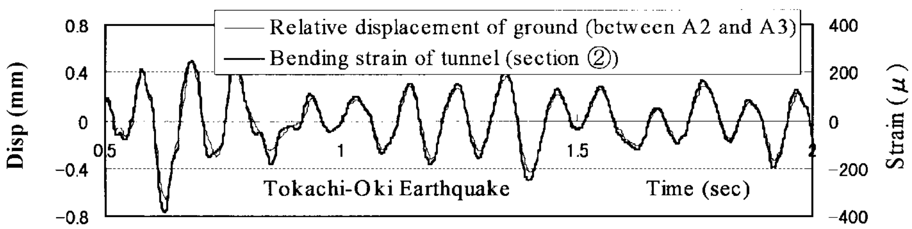



Fig. 13 Comparison between waveshapes of ground displacement and waveshapes of tunnel strain

deformation behavior of the shield tunnel is controlled by the surrounding ground.

## 5. Evaluation of numerical analysis methods

### *5.1 Dynamic analysis using ground-tunnel composite finite element model*

Test and dynamic analytical results of sectional forces of the tunnel under sinusoidal excitation with the resonant frequency of free ground are shown in Fig. 14. Test and dynamic analytical results of the sectional forces of the tunnel under the seismic excitation (taking the Tokachi-Oki Earthquake excitation, section ② of the tunnel as an example) are shown in Fig. 15. Above dynamic analytical results are found to be close to test data under both sinusoidal and seismic excitation, the usefulness of the two-dimensional dynamic finite element analysis is verified. However, for this analysis, input and output data are enormous and complex, and especially when seismic design of actual tunnels is performed, analysis takes a very long time, so it is necessary to improve analysis efficiency.

Based on knowledge from dynamic analysis of superstructures that the high frequency components of seismic waves only have a slight effect on the response of structures in the time history complex response analysis (JSCE 1989), by lowering the upper limit of the analysis frequency, case studies under seismic excitation were carried out. As a result, even when the upper limit of the analysis frequency is lowered to 20 Hz, the analytical results change little or not at all as shown in Fig. 16. Moreover, when a 20 Hz upper limit for analysis frequency is employed, the analysis time is only 1/4 of 100 Hz of analysis frequency.

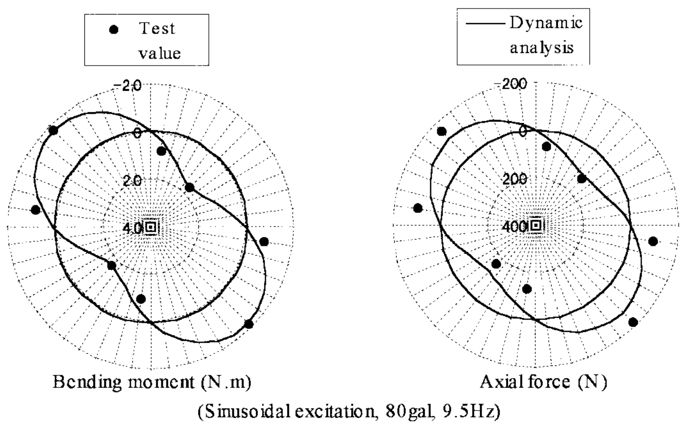



Fig. 14 Test and dynamic analytical results of maximum sectional forces of the tunnel

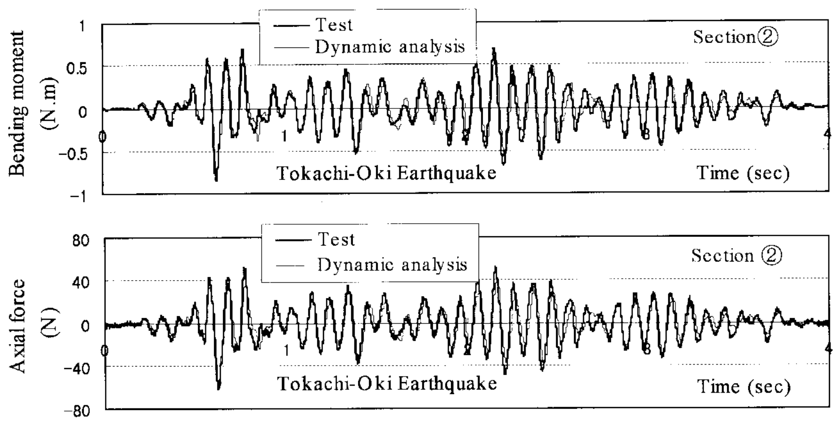



Fig. 15 Test and analytical results of sectional forces of the tunnel

### *5.2 Static analysis using ground-tunnel composite finite element model*

Taking the test case under sinusoidal excitation with the resonant frequency of the free ground as the example, static analysis using the ground-tunnel composite finite element model was carried out. In the analysis, it is found that analytical results of sectional forces on the tunnel correlate with the tunnel rigidities (EI and EA) as well as width L between the tunnel and ground boundary. In the analysis, by changing width L and the elastic modulus E of the tunnel structure, the case study under sinusoidal excitation with the resonant frequency of the free ground was carried out. As shown in Fig. 17, when the width of one-time outer diameter D of the tunnel is used, analytical results of sectional forces based on this method are in close agreement with test results. Moreover, as shown in Fig. 18, when the width of one-time outer diameter of the tunnel is used, relatively to the results of the dynamic analysis, the errors of both the maximum bending moment and the maximum axial force based on this method are less than 5%. It can be confirmed that the analytical

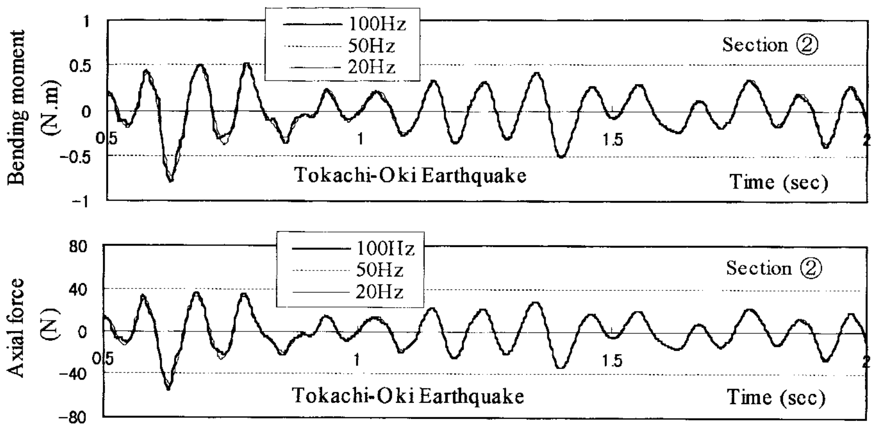



Fig. 16 Results of case study based on upper limit of analysis frequency

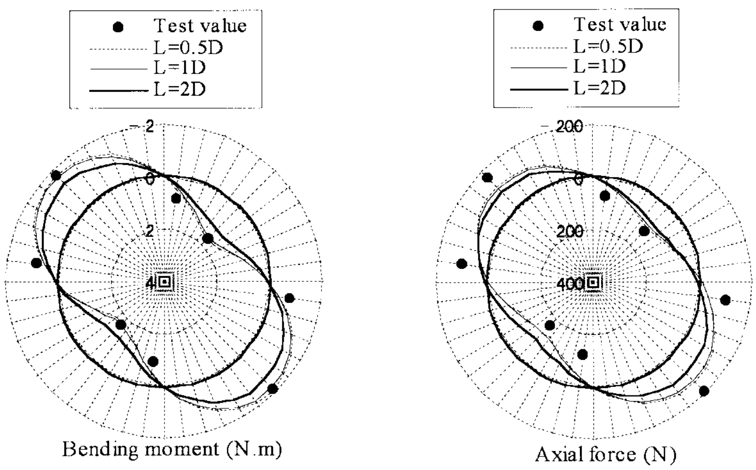
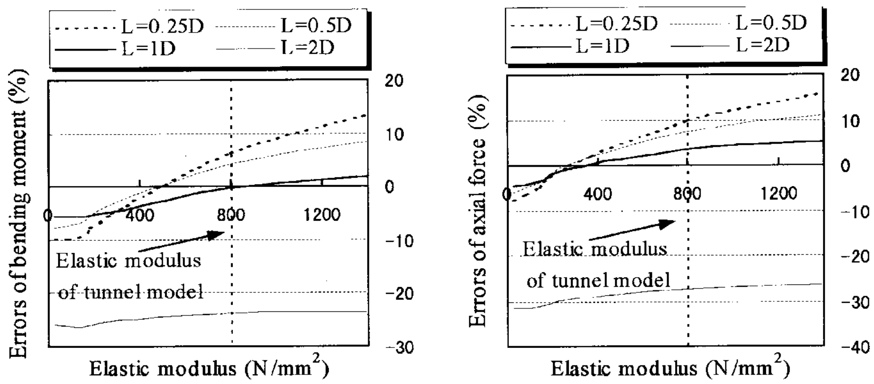



Fig. 17 Test and analytical results of maximum sectional forces of the tunnel (static FE model)



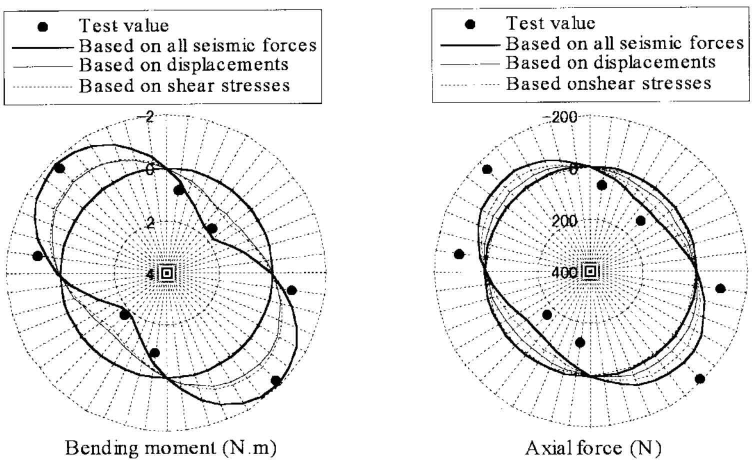

(Sinusoidal excitation, 80gal, 9.5Hz)

Fig. 18 Errors of sectional forces based on static FE model relatively to the dynamic analysis

results of sectional forces on the tunnel hardly correlate with the tunnel rigidities, if the width of one-time outer diameter of the tunnel analytical is used. The validity of the static analysis using ground-tunnel composite finite element model is verified as a seismic design method. It should be noted that in this modeling, the base of the ground was assumed to be a fixed boundary, so if the bottom condition of the ground differs from the prototype in this study, the analytical model proposed should be amended suitably.

### *5.3 Static analysis using beam-spring model*

Taking the test case under sinusoidal excitation with the resonant frequency of the free ground as the example, static analysis using a beam-spring model was carried out. Analytical results of sectional forces on the tunnel are shown in Fig. 19. From this figure, it is observed that analytical results using this method agree with test results, and the proportion of sectional forces based on




(Sinusoidal excitation, 80gal, 9.5Hz)

Fig. 19 Test and analytical results of maximum sectional forces of the tunnel (beam-spring model) ground displacements is approximately equal to that based on ground shear stresses. The validity of the static analysis using the beam-spring model is verified as a seismic design method. Because this method does not correlate with the tunnel rigidity and the ground boundaries, this method can be used directly in any type of ground condition.

## 6. Conclusions

The conclusions to be drawn from this study are as follows:

The dynamic behavior of the surrounding ground hardly changes even if a shield tunnel is constructed, and the shield tunnel follows the surrounding ground in its deformation under seismic motion. From these results, it can be confirmed that the seismic deformation method is adaptable to seismic design in the transverse direction of a shield tunnel.

The usefulness of the two-dimensional dynamic analysis is verified, In particular, this analytical method is significant for grasping dynamic characteristics of the ground and tunnel. However, as a seismic design method, it is necessary to improve the analysis efficiency.

For static analysis using ground-tunnel composite finite element models, when the width of one-time outer diameter of the tunnel is used, in similar ground conditions to this study, this method can be suggested as an analytical method for seismic design in the transverse direction of the shield tunnel. For static analysis using a beam-spring model, because this method does not correlate with the tunnel rigidities and the ground boundaries, it can be used directly in any type of ground condition as a useful seismic design method in the transverse direction of the shield tunnel.

Finally, in this study, all shaking table tests and numerical analyses were carried out within the elastic range and sliding displacement between the tunnel and the ground did not occur, therefore, under low-level seismic motion, the two static analysis methods proposed can be used directly in seismic design in the transverse direction of a shield tunnel. However, if the contact condition between the tunnel and surrounding ground or a nonlinear ground spring is considered, it is possible that the static analysis methods proposed can be used even under comparatively high-level seismic motion.

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