DYNAMIC BEHAVIOR IN TRANSVERSE DIRECTION OF SHIELD TUNNEL WITH CONSIDERING EFFECT OF SEGMENT JOINTS

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SUMMARY

This paper describes the dynamic behavior and the seismic design method in the transverse direction of shield tunnels with considering the effect of segment joints. A series of shaking table model tests was carried out, and the dynamic 2-D FEM analysis and the static analyses based on the seismic deformation method were performed. The investigation concerns the response behavior of tunnel and ground, the interaction between tunnel and ground, the modeling of segment joints, and the evaluation of different seismic design methods. In the model tests, materials of ground and tunnel were chosen according to the similarity law, and a double-track subway shield tunnel assembled by using the straight joint was considered as the test prototype. In the static analyses based on the seismic deformation method, the time when the largest displacement difference of top and bottom of the tunnel appears is considered, analytical results of sectional forces are found to be close to the test values. Results of the investigation indicate that the seismic deformation method with the static FEM or the beam-spring model can be suggested as a practical seismic design method of shield tunnels with considering effect of segment joints.

INTRODUCTION

Recently, complex and large cross-sectional shield tunnels have been increasing in number, and required seismic design cases in the transverse direction are becoming more and more in Japan. Authors have carried out an investigation on the basic dynamic behavior in the transverse direction of shield tunnels with disregarding the effect of segment joints [1]. However, a shield tunnel is a cylindrical structure that is made by assembling segments by the use of joints. Due to "joints" of segments, the dynamic interaction between the ground and the tunnel becomes very complicated. Further investigation about the seismic behavior including the tunnel structure and the surrounding ground as well as rational design methods with considering the effect of segment joints is necessary. For these reasons, based on past investigation, a series of shaking table model tests with considering the effect of segment joints was carried out and static analyses as well as dynamic analyses on the tests were performed.

SHAKING TABLE MODEL TEST

Prototype Of Tunnel And Ground:

A double-track subway shield tunnel without the secondary lining was considered as the test prototype, whose outer diameter is 10.0m. The shield tunnel is assembled by the segments (RC flat plate type, width and thickness is 1m and 0.4m, respectively) by using the straight joint. It is assumed that the shield tunnel is located at a poor alluvium (layer thickness is 30m, N-value of Standard Penetration Test is 3), and the overburden is 14m, moreover, the basis is a very hard diluvium (N-value of standard penetration test is greater than 50) which can be considered as a rigid-body in the seismic design.

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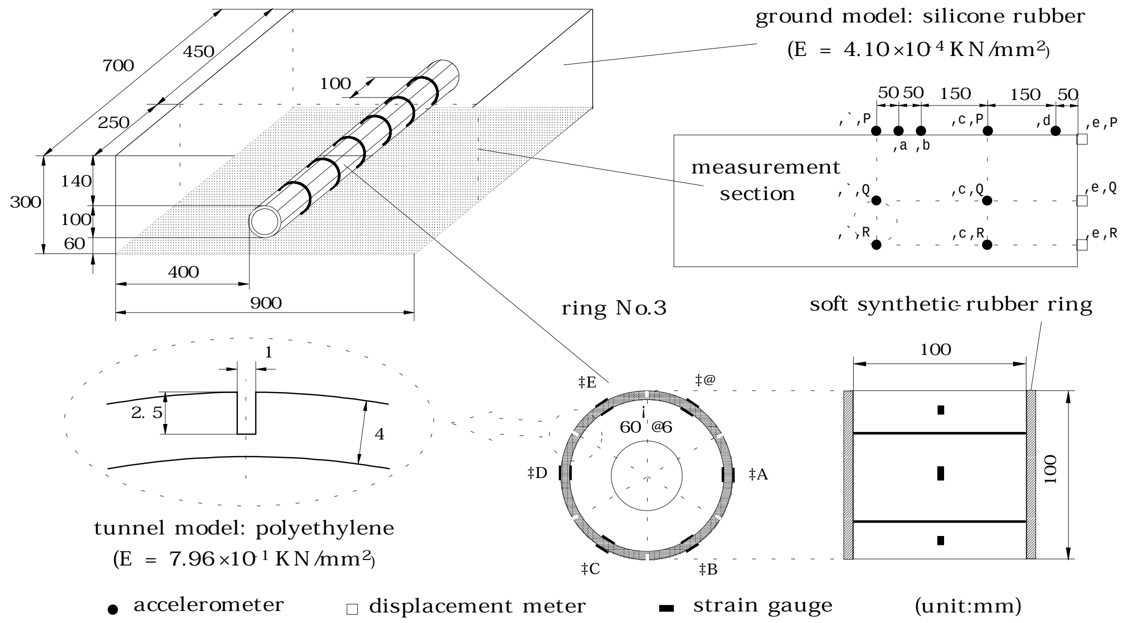

Figure 1: Details of model and measurement points.

Similarity Law:

In the model tests, materials of ground and tunnel were chosen according to the similarity law. The similarity law of the physical quantity is introduced as follows. First, It is assumed that the inertial force and the elastic force in the ground is the mutually independent dominant physical quantity. They can be shown in equation (1) and equation (2) using mass density ρ, length l, time t, strain ε and elastic modulus E.

Inertial force: $F_i = \rho \cdot l^4 \cdot t^{-2}$ (1)

Elastic force: $F_s = \varepsilon \cdot E \cdot l^2$ (2)

The similar relation between prototype and model is shown as Equation (3) by using the ratio of these forces:

$$\frac{\rho_m \cdot l_m^2}{\varepsilon_m \cdot E_m \cdot t_m^2} = \frac{\rho_p \cdot l_p^2}{\varepsilon_p \cdot E_p \cdot t_p^2} \tag{3}$$

Where, subscript m and p denotes model and prototype, respectively.

Next, the similarity law of mass density, length and time is considered as the basic similarity law respectively, which is shown in Equation (4).

$$P = \frac{\rho_m}{\rho_p}, \quad L = \frac{l_m}{l_p}, \quad T = \frac{t_m}{t_p} \tag{4}$$

Finally, we fix that dimensionless quantity ε_m and ε_p is equivalence, then the similarity law of elastic modulus (E_m/E_p) and similarity law of acceleration (a_m/a_p) can be introduced as following Equation (5).

$$\frac{E_m}{E_p} = \frac{L \cdot P^2}{T}, \quad \frac{a_m}{a_p} = \frac{P}{T^2} \tag{5}$$

Model Of Tunnel And Ground:

Alluvium ground was simulated by silicone rubber. Because a shield tunnel assembled by using the straight joint is considered as the test prototype, the shield tunnel was simulated by a polyethylene ring, in which a set of transverse joints of a segment was simulated by a longitudinal groove, and circumferential joints of segment

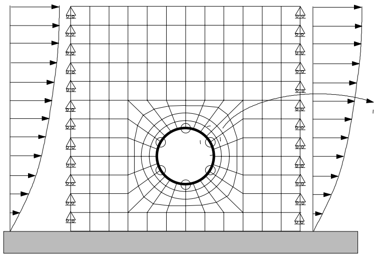

Figure 2: Static FEM model.

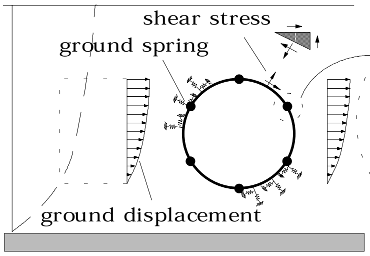

Figure 3: Beam-spring model.

rings were neglected. Moreover, the tunnel model was divided into mutually independent 7 rings whose intervals were filled by soft synthetic-rubber rings, so that the influence of longitudinal ground boundaries on the central part of the model can be reduced possibly. Details of the test model and measurement points are shown in Figure 1.

Outline Of Model Tests:

Shaking table tests were carried out for both the free ground model and the tunnel-soil composite model. The bottom of the model was fixed to the shaking table, and the unidirectional horizontal exciting wave was inputted from the shaking table in the transverse direction. First, the model was excited by the sinusoidal wave, in which, the maximum acceleration was 80gal, and the frequency was changed from 2Hz to 50Hz. Secondly, Tokachi-Oki earthquake record (Hachinohe), El-centro earthquake record and Hyougo-ken nambu earthquake record was used as the exciting seismic wave, respectively, whose time base was shortened to 1/10 in real time, amplitude was 300gal.

Measurement sensors were installed in the central section (ring No.3) of the test model. Accelerometers, which record the absolute time-history accelerations, were put on the shaking table, the ground surface and the underground. Strain gauges, which record the time-history strains of the tunnel, were put on 6 points of the cross-section of the tunnel model; moreover, the bending strain component and the axial strain component of each measurement point was measured respectively. The horizontal time-history displacements of the sides of the ground model were measured by laser displacement meters.

OUTLINE OF NUMERICAL ANALYSIS

2D dynamic FEM analysis:

In order to check accuracy of the tests and to grasp dynamic characteristics of ground and tunnel, the numerical simulations with the dynamic plain strain FEM were carried out on the shaking table model tests. The ground model and the tunnel model was modeled as plane isoparametric elements and beam elements, respectively. Moreover, transverse joints of the segment were simulated by short beam elements that were lowered in tension-compression rigidity and the bending rigidity. The basis was considered as a rigid-body and the sides of the ground as free boundaries. The time-history response analysis using complex response method [2] was employed. The wave damping of the ground model was evaluated by using test resonance curves of the ground acceleration, but the wave damping of the tunnel model was neglected in the analysis. Input excitations were time-history accelerations of the shaking table, which had been measured from the test.

Analysis based on seismic deformation method:

Analysis with static FEM model:

On the basis of the concept of the seismic deformation method, the analysis using the static tunnel-ground composite FEM was proposed [5], and the analytical model is shown in Figure 2. In this model, the modeling of the ground and the tunnel is same as that of the dynamic FEM analysis, but level roller supports were installed in the side boundaries. The time when the largest displacement difference of top and bottom of the tunnel appears is set in the analysis. The horizontal displacements of the free ground, which were calculated using the time-history dynamic analysis, were inputted statically through nodes of the side boundaries.

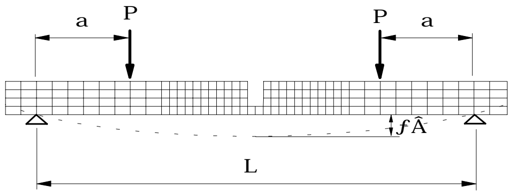

Figure 4.

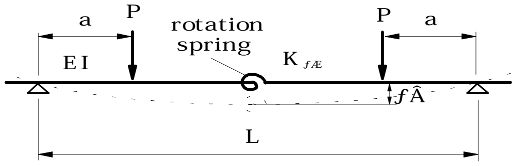

Figure 5.

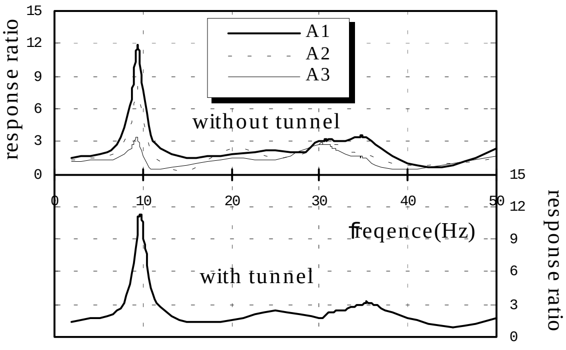

Figure 6: resonance curves of ground accelerations (based on test).

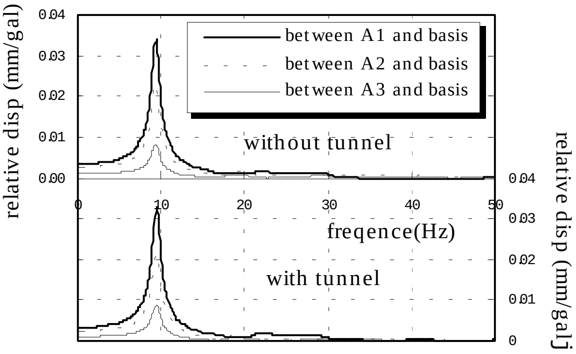

Figure 7: resonance curves of ground relative displacement (based on dynamic analysis).

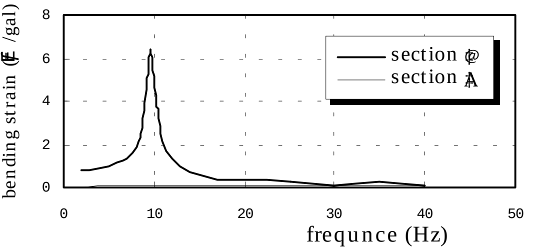

FIGURE 8: RESONANCE CURVES OF BENDING STRAIN

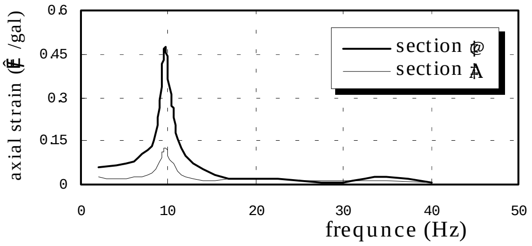

FIGURE 9: RESONANCE CURVES OF AXIAL STRAIN

Analysis with beam-spring model:

The analytical model of the shield tunnel is shown in Figure 3. The tunnel was simulated by the beam-spring structural model in which the beam elements and rotation spring elements were positioned alternately [3]. The interaction between ground and tunnel was simulated by radial ground springs and tangential ground springs. The time when the largest displacement difference of top and bottom of the tunnel appears is set in the analysis. Seismic forces due to relative ground displacements and ground shear stresses, which were figured out by using the time-history dynamic analysis of the free ground, are employed in the analysis. The horizontal displacements of the free ground were inputted statically through the ground springs. In the meanwhile, the ground shear stresses were directly inputted statically [4].

Because the sliding displacement between the tunnel and the ground has been restricted in the tests, it can be assumed that ground springs are linear springs. Hence, the plate-loading test is concluded to determine ground spring constants.

According to the relationship (as shown in Figure 5) between displacement and force for the beam with a groove (which simulated the a set of transverse joints of a segment in the tests, see Figure 1), rotation spring constant K_{θ} of a set of transverse joints of a segment can be determined by Equation (6),

$$K_{\theta} = \frac{6E\cdot I\cdot P\cdot a\cdot L}{24EI\cdot\delta - P\cdot a(3L^2 - 4a^2)} \tag{6}$$

where, E, I, P, a, L and δ denotes elastic modulus, geometrical moment of inertia, load, distance between loading point and supporting point, distance between loading point and displacement of the center position of the beam, respectively. In the meantime, the displacement of the center position can be calculated by using a FEM (see modeling of Figure 4).

CONSIDERATION ABOUT DIFFERENT ANALYSIS METHODS

Dynamic response behavior of tunnel and ground:

The resonance curves of ground accelerations are shown in Figure 6, and the resonance curves of ground relative displacement in Figure 7, the resonance curves of strains in the tunnel in Figure 8 and Figure 9. From these figures, It can be observed that the resonance curves of ground accelerations and the resonance curves of ground relative displacement change little or no, even if a shield tunnel is constructed in the ground. In the meantime, the resonant frequency of strains in the tunnel is similar to that of the ground. These results show that the dynamic behavior of the tunnel is related close to the surrounding ground.

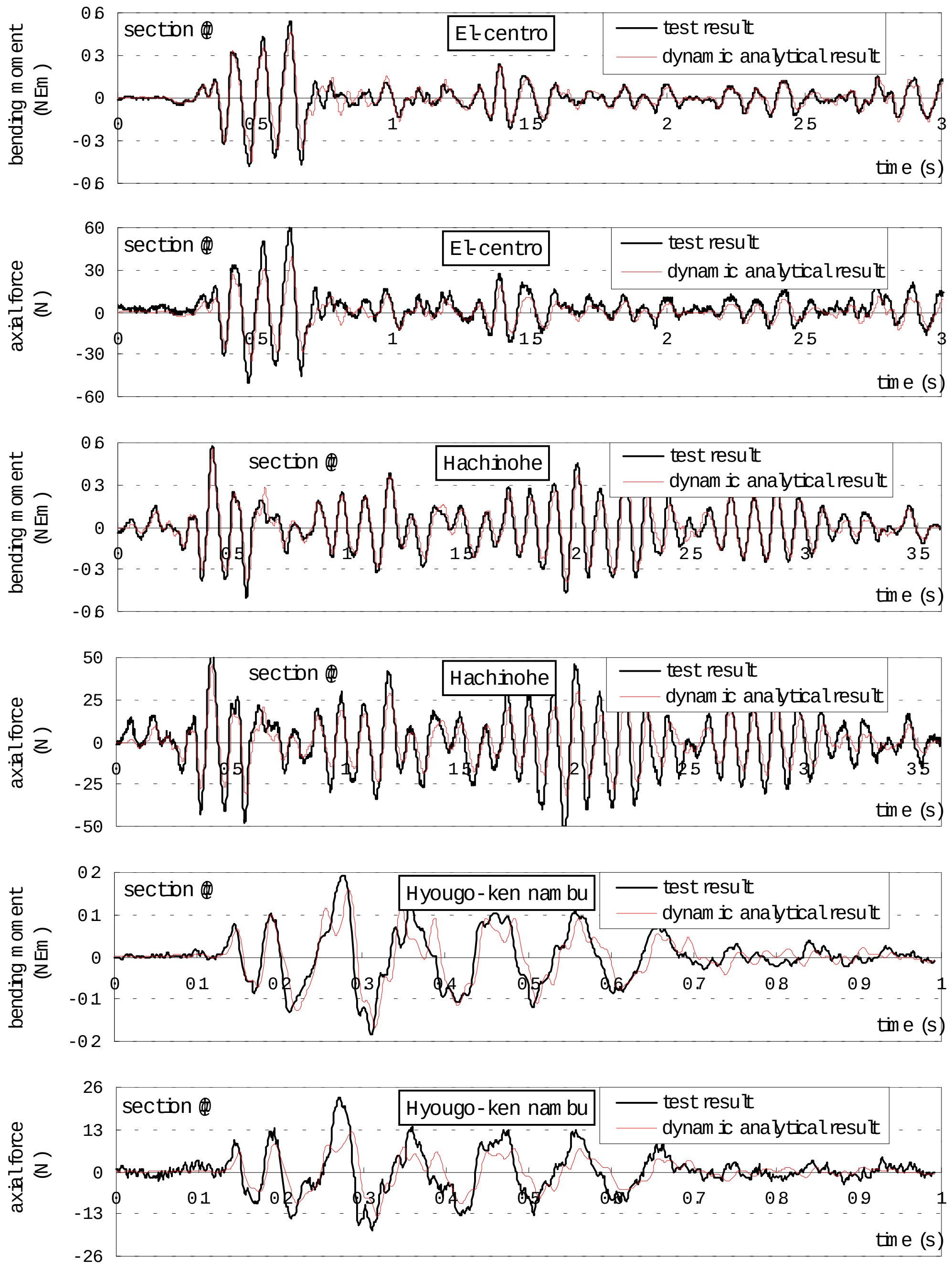

Figure 10: sectional forces in the tunnel based on tests and dynamic analysis.

2D FEM dynamic analysis:

Based on the knowledge that the high frequency component of seismic wave does not affect the response of a tunnel almost, by lowering the upper limit of the analysis frequency, a case study under the seismic excitation was carried out. As a result, even the upper limit of the analysis frequency is lowered to 20Hz, analytical results change little or nothing, Moreover, when the upper limit of the analysis frequency 20Hz is used, analysis time is only 1/4 of 100Hz. Test and dynamic analytical results for the sectional forces of the tunnel under the seismic excitation (take one of sections for example) are shown in Figure 10. Dynamic analytical Results are found to be close to test data, the usefulness of the 2D FEM dynamic analysis is verified. However, for this analysis, input and output data are enormous and complex, in addition, analysis time is very long, as a design method the

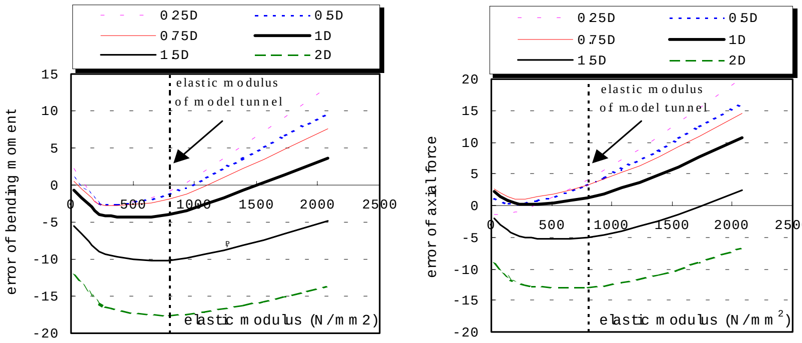

Figure 11: Error of sectional forces based on static FEM relatively to the results of the dynamic analysis.

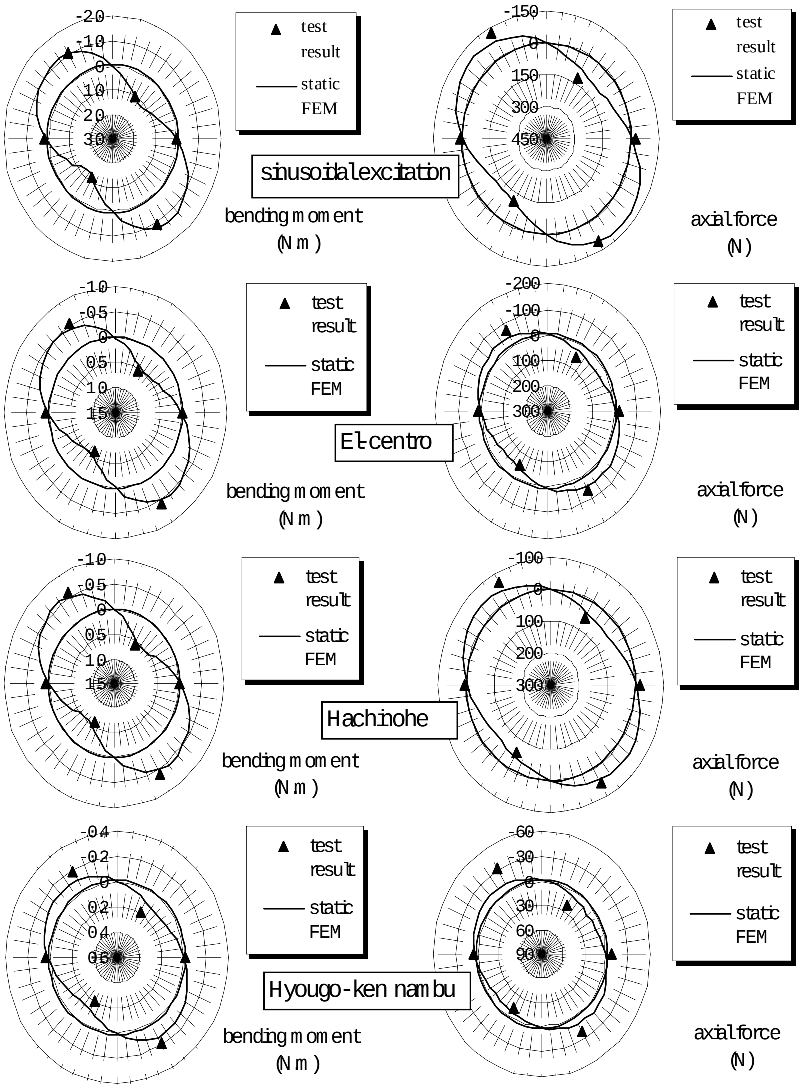

Figure 12: Comparison between test results of sectional forces

analysis efficiency is bad.

Seismic deformation method with static FEM model:

For this method, in general, analytical results are correlated with the width of the side ground and the tunnel rigidity. Therefore, by changing parameters of the width of the side ground and the tunnel rigidity, a case study with the sinusoidal excitation under the resonant frequency was carried out. As shown in Figure 11, when a side ground range of 0.5 ~ 1 tunnel diameter (D) is considered, within elastic modulus of the model tunnel the error of both the maximum bending moment and the maximum axial force (relatively to the results of the dynamic analysis) is less than 5%. For this reason we used 1 tunnel diameter in the analysis with the static FEM model.

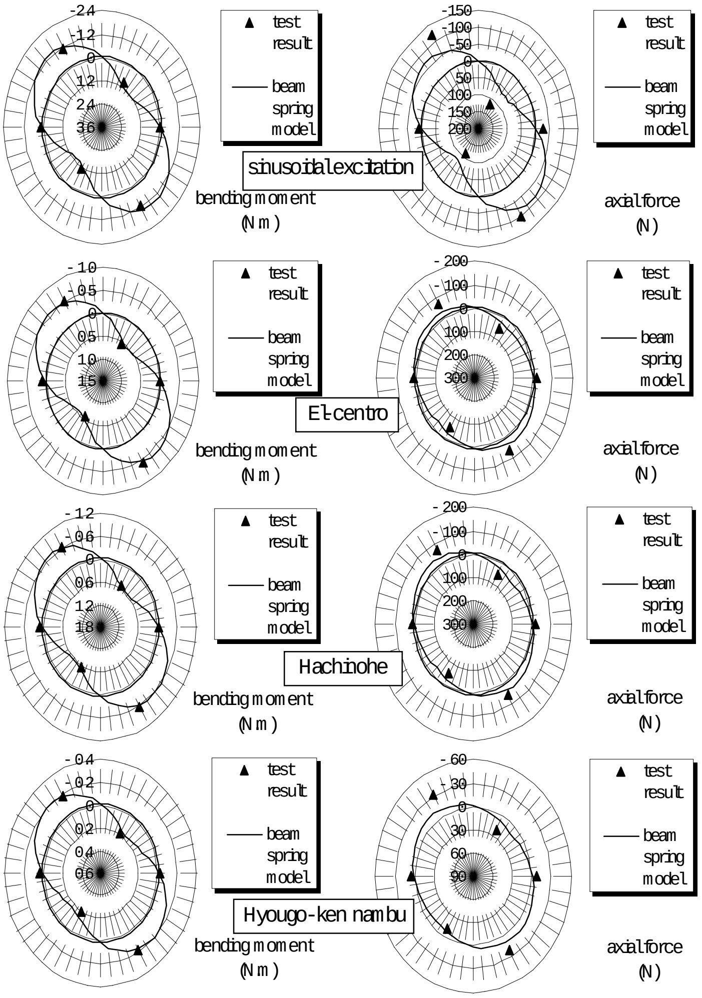

Figure 13: Comparison between test results of sectional forces

When the largest displacement difference of top and bottom of the tunnel appears (in this time the maximum sectional forces of the tunnel appear), test and analytical results for sectional forces of the tunnel under the sinusoidal excitation and the seismic excitation are shown in Figure 12. Analytical Results are found to be close to test data, the validity of the seismic deformation method with 2D static FEM model is verified.

Seismic deformation method with beam-spring model:

When the largest displacement difference of top and bottom of the tunnel appears (in this time the maximum sectional forces of the tunnel appear), test and analytical results for sectional forces of the tunnel under the sinusoidal excitation and the seismic excitation are shown in Figure 13. From this figure, It is observed that analytical results of the bending moment using this method agree with test results, and analytical results of the axial force agree with test results approximately. Generally the seismic deformation method with beam-spring model has a good accuracy, and the effect of segment joints can be evaluated sufficiently by using the rotation spring element in this method. However, seismic forces due to both relative ground displacements and ground shear stresses should be considered in the analysis.

CONCLUSIONS

1. The shield tunnel assembled by using the straight joint has a high flexibility in the transverse direction. The shield tunnel follows the surrounding ground in the dynamic behavior; the dynamic behavior of the surrounding ground does not almost change even if a shield tunnel is constructed in the ground. This result confirms that the seismic deformation method can be used as a possible approach for the seismic design in the transverse direction of the shield tunnel without a secondary lining.
2. The dynamic behavior of the shield tunnel assembled by using the straight joint can be analyzed by using the dynamic 2D FEM. The usefulness of the 2D FEM dynamic analysis is verified by the shaking table tests, especially, It is significant to grasp dynamic characteristics of ground and tunnel with this analytical method. However, as a seismic design method, it is necessary to improve the analysis efficiency.
3. For the seismic deformation method based on the static FEM analysis, the effect of segment joints can be evaluated sufficiently by using a beam element lowered in the tension-compression rigidity and the bending rigidity. When the side ground range of 0.5 ~ 1 tunnel diameter is considered, analytical results of sectional forces are found to be close to the test values. In a similar ground condition to this study, this method can be suggested as an analytical method for the seismic design of a shield tunnel with considering the effect of segment joints.
4. With using the seismic deformation method based on the beam-spring model, analytical results of sectional forces agree with test results. The effect of segment joints can be evaluated sufficiently by using the rotation spring element in this method. However, seismic forces due to both relative ground displacements and ground shear stresses should be considered in the analysis. In any case of ground condition, this method can be used easily as a useful method for the seismic design of a shield tunnel with considering the effect of segment joints.

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