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Tests on dynamic interaction between foundations

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ABSTRACT: Model tests were carried out using a ground model made of silicone rubber to investigate the dynamic interaction effects between buildings through the soil and to verify analysis tools. The dynamic behavior of the two foundations which are parallel or perpendicular to the direction of the excitation is evaluated compared with that of the single foundation. The test results were calibrated with the analytical results based on two dimensional finite element method (FEM) and three dimensional boundary element method (BEM).

1 INTRODUCTION

Analysis tools for evaluating the effects of dynamic interaction between adjacent structures through the soil have become available these days. However, experimental data to verify the analysis tools still lack. To provide such data, model tests were carried out using the ground model made of silicone rubber which has excellent elastic characteristics.

2 OUTLINE OF TEST

The ground and foundation models are shown in Fig.1. The ground model is made of silicone rubber with its Young's modulus $E=3.0kg/cm^2$. The ground model is a cylinder with diameter of 300cm and height of 70cm and has an 18cm deep rectanglar pit at its center. The dimension of the pit is 40cm x 70.5cm at bottom and 76cm x 106.5cm at the top surface level. The side slope angle is 45 degrees. It has 180 brass bars around its circumferential edge to restrain vertical deformation of the ground model during shaking table test. Two foundation models of the same dimensions (30x30x18cm) are made of aluminum. The dimensions and material properties of the ground model are determined considering typical reactor buildings on soft rock site in Japan. The foundations are bonded to the bottom of the pit of the ground model. The gap between the foundations is 5mm.

Three stages of test were carried out. Firstly the ground model without foundation was tested. Then the ground model with single foundation was tested. Finally the ground model with two foundations was tested. Impulse hammering and shaking table tests were performed for two directions. One is perpendicular to the direction of the array of the foundations (X direction) and the other is parallel to that (Y direction). The hammering tests were carried out to evaluate the vibration characteristics of the foundations on the ground and obtain the impedance functions. The excitation was applied by an impulse hammer equipped with a load cell at its tip. The shaking table tests were also carried out applying sinusoidal waves, and the foundation input motions were derived.

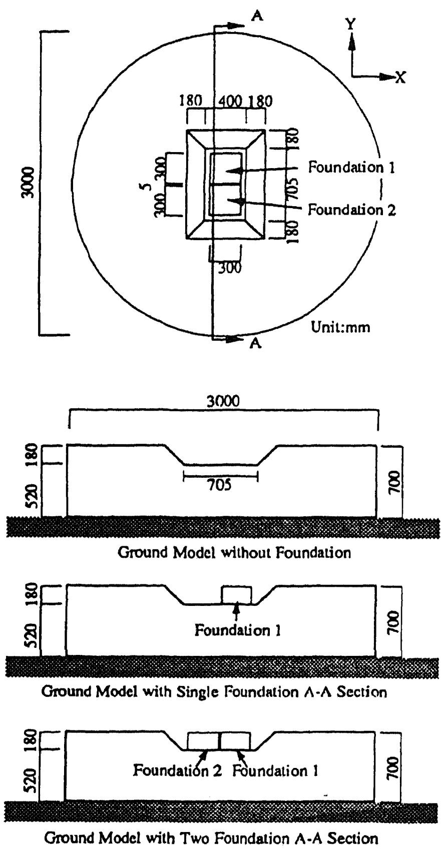


Fig.1 Ground and foundation models

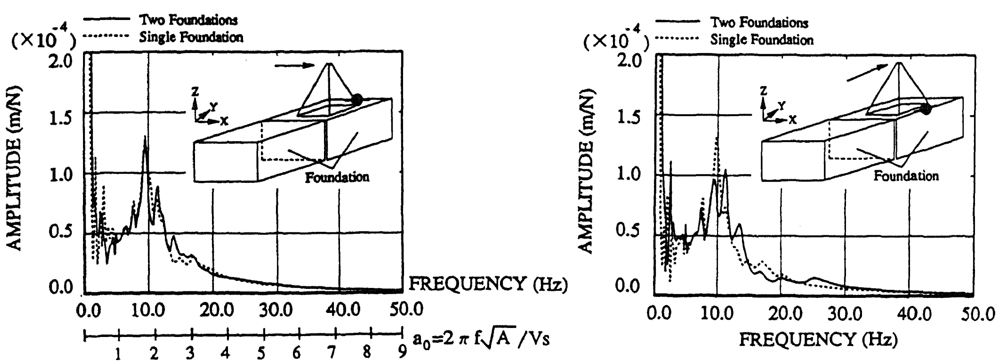
3 TEST RESULTS

3.1 Transfer functions and vibration modes

The transfer functions of displacement versus applied force obtained by the hammering test are shown in Fig.2. 50.0 Hz is equivalent to 9.0 of non dimensional frequency $a_0 = 2\pi f\sqrt{A}/Vs$ (A:area of foundation, Vs:shear velocity of ground model). Because the hammering pulse does not have enough power, the accelerometers could not catch accurate data in low frequency range. The noise in a range of lower than 5 Hz in the Fig.2 is due to this reason. The several small peaks other than the peak at fundamental frequency of soil structure interaction system(around 10 Hz) are mainly due to reflected waves from the bottom boundary of the silicone ground model. Little effects due to the presence of adjacent foundation are observed especially in the case of x directional hammering test. Figure 3 shows the transfer function of the top of the foundation versus the average motion at the pit bottom of the ground model without foundations in the shaking table test. Somewhat larger effects of the adjacent foundation was observed in the shaking table test, because the foundation input motions are also influenced in the shaking table test.

Figure 4 shows the first vibrational modes of the soil pressure under X and Y directional shaking table tests. Though the effects of the adjacent foundation on acceleration or displacement are relatively small, those on soil pressure are significant. The soil pressure at the bottom of the foundation closer to the adjacent foundation is considerably smaller than that at the opposite side of the foundation. These phenomenon are clearer for Y directional (parallel to the array of the foundations) excitation. Both of two foundations behave like one large foundation, because the gap between the foundation is so small(5mm).

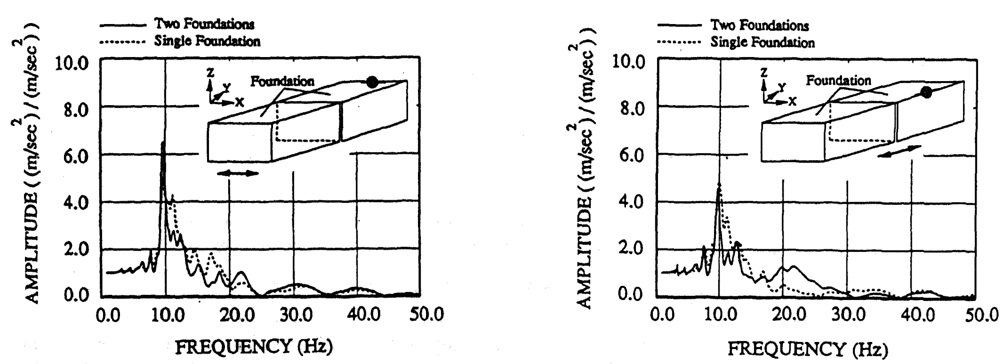
Figure 5 shows the transfer functions of soil pressure at bottom of foundation versus average horizontal acceleration of pit bottom. The soil pressure for the two foundations test shows smaller values than that of the single foundation test in Y directional excitation. In X directional excitation the difference of the soil pressures between both tests is not clear.



(a)X directional excitation

(b)Y directional excitation

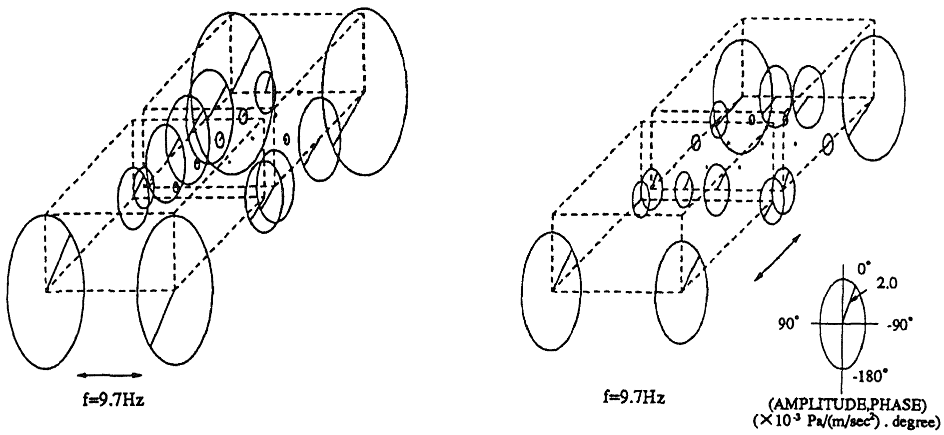
Fig.2 Transfer functions of horizontal displacement at top of foundation versus applied load on top of attachment



(a)X directional excitation

(b)Y directional excitation

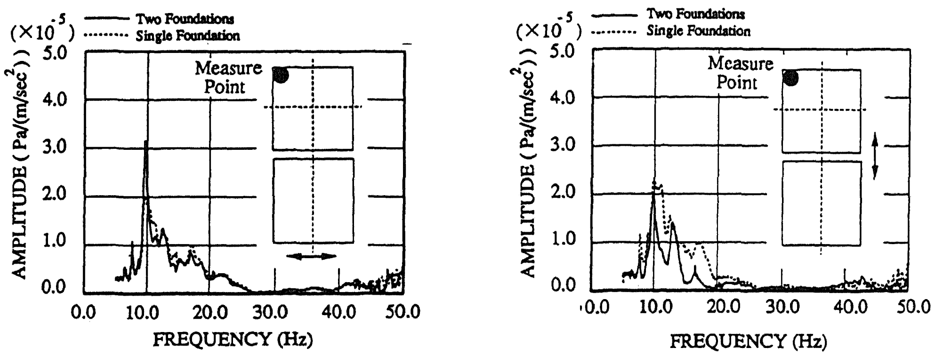
Fig.3 Transfer functions between pit bottom and top of foundation



(a)X directional excitation

(b)Y directional excitation

Fig.4 Vibration modes of soil pressure for shaking table test



(a)X directional excitation

(b)Y directional excitation

Fig.5 Transfer functions of soil pressure at bottom of foundation versus average horizontal acceleration of pit bottom

3.2 Impedance Functions and Foundation Input motions

a. Impedance functions

To obtain the every element of impedance function of the cross interaction, the locations of the loading point by the hammer were chosen as is illustrated in Fig.6. Though the impedance matrix of cross interaction consists of 12x12 elements, the independent elements can be reduced to 24 owing to the symmetrical nature along X and Y axes. These 24 elements can be divided into the two independent matrices. One matrix has 12 symmetrical elements and the other has 12 non-symmetrical elements.

Figure 7 shows the impedance functions of sway element(K^{11}_{HH}) and rocking element(K^{11}_{MM})for three cases (single foundation, Y-directional cross interaction, X-directional cross interaction). Referring to the data processing method of transient response (Mita et al. 1989), the reflected waves from the boundary are removed in the procedure to obtain impedance functions from the test data. The smooth impedance functions in the figures are regarded as those for the uniform half space. The sway and rocking elements ,especially Y-directional elements, of the impedance function increase due to the existence of the adjacent foundation. The fluctuation in the lower frequency region is caused by the same reason as that in Fig. 2.

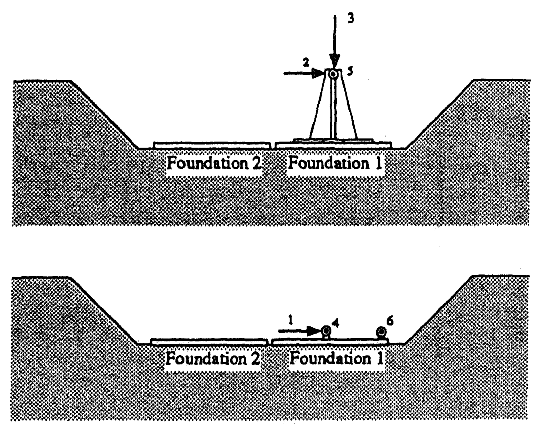
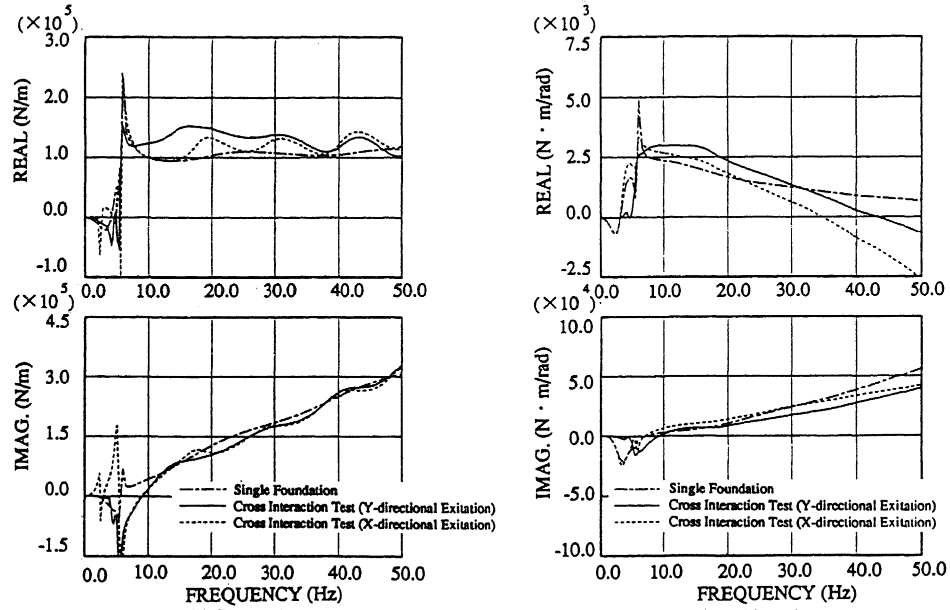


Fig.6 Location of loading points on foundation



(a) Sway element

(b)Rocking element

Fig.7 Comparison of impedance functions

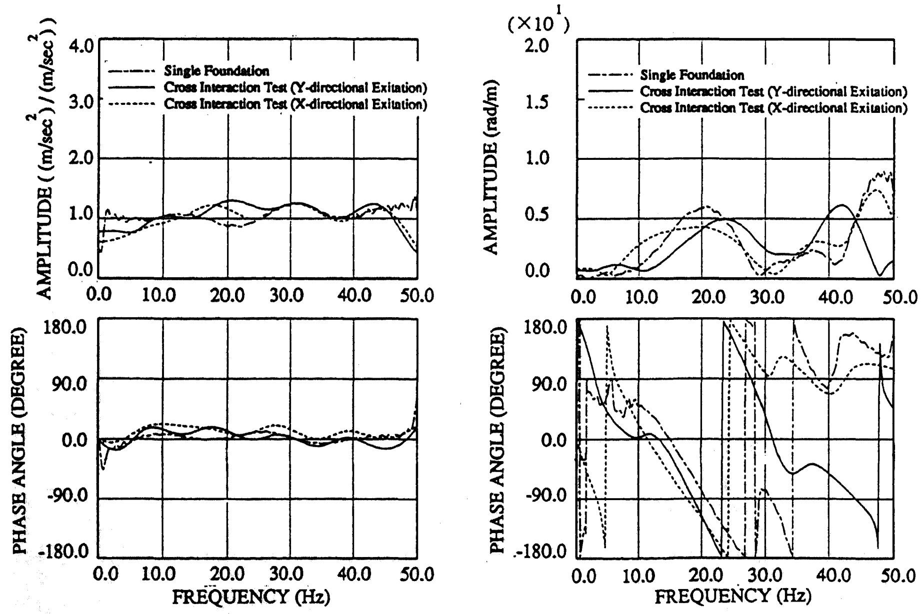
b. Foundation input motions

The foundation input motion is defined as the motion of massless foundation and derived as following.

$$\{U^*\} = \{U\} - \omega^2[k(\omega)]^{-1}[m]\{U\}$$

$\{U^*\}$: Foundation input motion
$\{U\}$: Motion of foundation

Figure 8 shows the transfer function of the foundation input motion versus the movement of the average motion of the pit without the foundations. Each horizontal component of the foundation input motion has an amplitude of almost 1.0 and phase of nearly zero. Rocking component exists in each case due to the existence of the pit. No significant change is observed except the shift of phase to lower frequency due to existence of the adjacent foundation.



(a) Sway

(b) Rocking

Fig.8 Comparison of foundation input motions

4 COMPARISON BETWEEN TEST AND ANALYSIS

The impedance functions derived from the data of the hammering test were compared with the analytical results of two dimensional FEM (Fukuwa and Nakai 1989) and three dimensional BEM(Yosida and Kawase 1988). The FEM model is shown in Fig.9, and three dimensional effects associated with out-of-plane direction is taken into this analysis, namely dashpots are added to each finite element of the ground model. In the BEM analysis the excavated portion of the ground is not taken into consideration and only the ground portion adjacent to the foundations is modeled with mesh. The material properties derived from the material tests and used in the analyses are listed in Table 1. The material properties for BEM analysis are the same as those derived from the material test of silicone rubber, but those for FEM analysis are modified to fit the results of the shaking table test for the ground model without the foundations.

Figure 10 shows the impedance functions of sway and rocking elements comparing the analytical results with the test result. Figure 11 shows those of cross interaction elements. Though the analytical results of three dimensional BEM agree well with the test results, the impedance function of two dimensional FEM differ from test results. Figure 12 compares the test and FEM analytical results for the transfer functions of acceleration at the foundation versus that at pit bottom. Though the considerable differences are observed between impedance functions of the test and those of FEM, the transfer functions of FEM coincide well with those of the test.

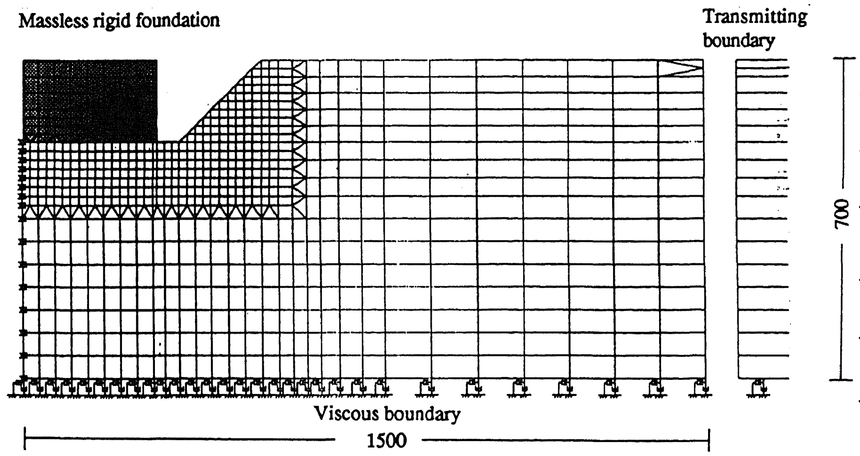
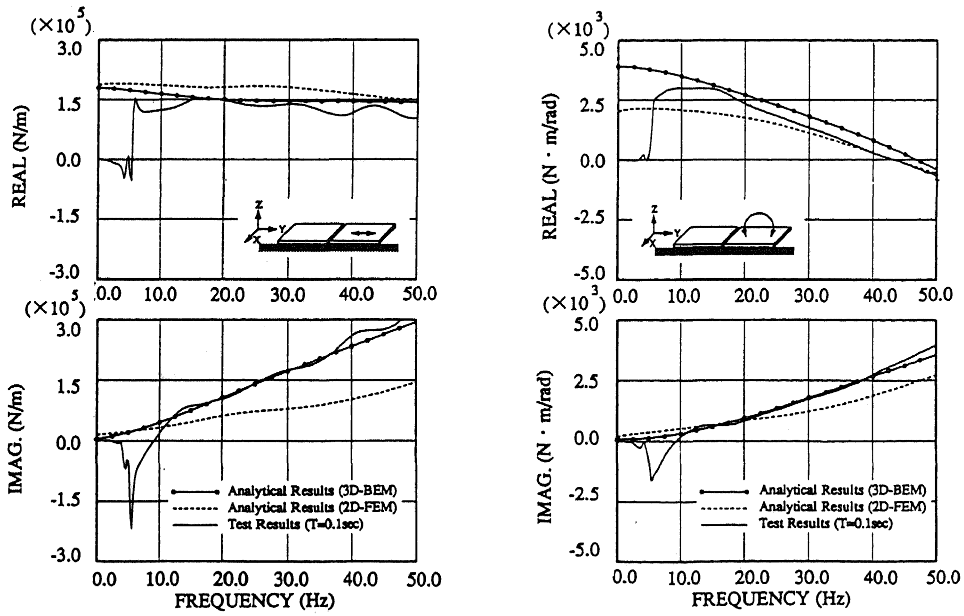


Fig.9 Model for 2 dimensional FEM

unit:mm

Table.1. Material Properties of Ground Models

	Material Test	FEM
Young's modulus E(Pa)	3.40×10^{5}	2.77×10^{5}
Poisson's ratio ν	0.49993	0.49
Shear wave velocity V_s (m/sec)	10.76	9.74
Density ρ (kg/m^3)	1.0×10^{3}	1.0×10^{3}
Damping factor h	0.03	0.034



(a)Sway element

(b)Rocking element

Fig.10 Comparison of impedance functions between test and analyses

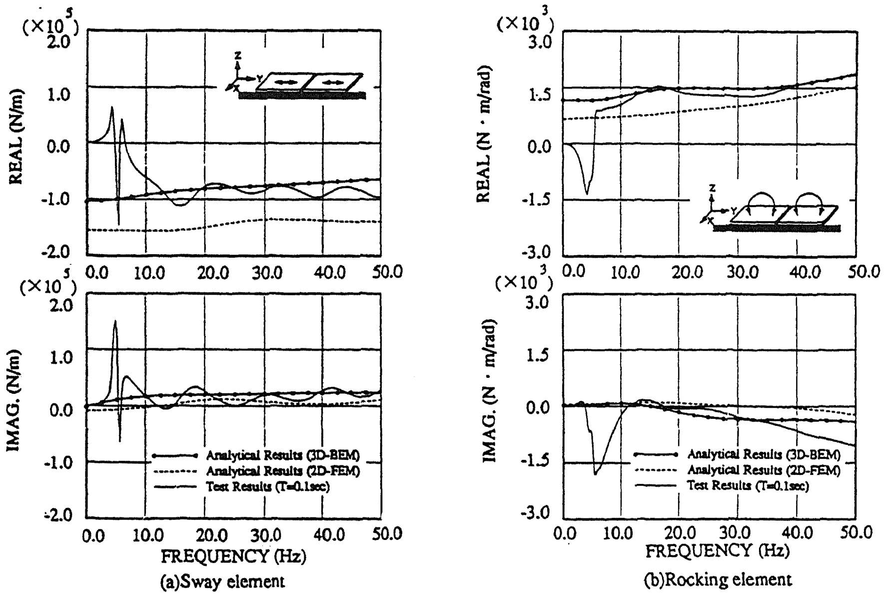


Fig.11 Comparison of impedance functions for cross interaction between test and analyses

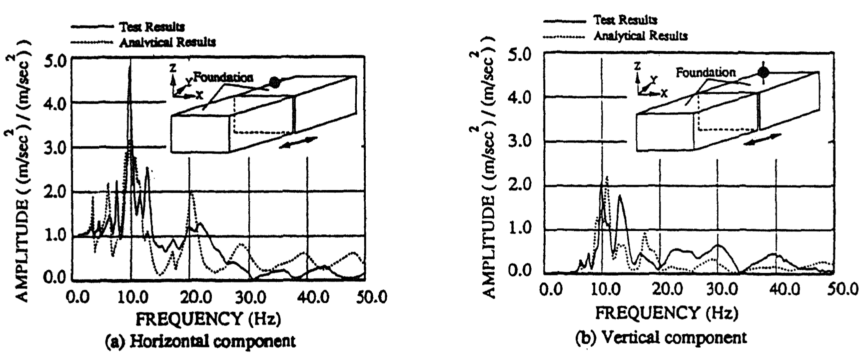


Fig.12 Comparison of transfer functions between test and FEM

5 CONCLUSIONS

Experiments to evaluate dynamic interaction effects of the foundation-soil-foundation system were performed using silicone rubber ground model and the foundation models made of aluminum. The test results were compared with analytical results.

The transfer functions of displacement versus applied force by the hammering test indicate little effects due to the existence of adjacent foundation especially in the case of x directional test. Somewhat larger differences were observed in the shaking table test. Though the effects of adjacent foundation on acceleration or displacement are relatively small, those on soil pressure are significant.

The analytical impedance functions of three dimensional BEM agree well with the test results. The analytical transfer functions of FEM roughly agree with test results.

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